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Assessing Mineral Resource Scarcity in a Circular Economy Context

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ABSTRACT

Due to humanity's dependence on metal resources there are growing concerns regarding impacts related to their potential scarcity, both for current and future generations. The vision of a more circular economy suggests that extending the functional use of metals through measures aiming for resource-efficiency (RE) such as increasing technical lifetime, repairing and recycling could reduce mineral resource scarcity. However, evidence of this is limited. In addition, there is limited understanding regarding on what principles metals can be prioritized when assessing mineral resource scarcity.

The aim of this thesis is to provide knowledge on mineral resource scarcity impacts of RE measures applied to metal-diverse products and on which conditions they depend. This is achieved by: 1) studying RE measures from a life cycle perspective; 2) comparing principles of prioritization between metals on which mineral resource scarcity impacts are assessed and 3) analysing how such principles (of prioritization) can affect conclusions regarding RE measures applied to metal-diverse products. The research is conducted through case studies, syntheses of literature and method development within the methodologies of life cycle assessment, material flow analysis and criticality assessment.

Results indicate that effects of RE measures depend on a number of product characteristics and real-world conditions. RE measures can both increase and decrease mineral resource scarcity impacts compared to business as usual and effects vary greatly between metals. RE measures based on use extension e.g. reuse of laptops, repair of smartphones, and increasing technical lifetimes of LED lighting, have been indicated to reduce impacts through two principal features: use extension, and, increased functional recycling. However, there are risks of increasing mineral resource scarcity impacts if RE measures require additional metal use, product use extensions are short and if functional recycling is lacking. For example, repair of smartphones risks to increase the use of metals in commonly replaced components such as screens.

Because of the varying effects on different metals, implementation of RE measures requires prioritizing some metals over others. The principles of prioritization give diverging results, and, are sometimes unclear and methodologically inconsistent. The thesis clarifies how they relate to concepts such as depletion, criticality, rarity and scarcity. Further it suggests that, although mineral resources are fundamentally stock resources, they can pose stock, fund and flow problems. Distinguishing between these different problems in distinct methodologies is conducive to purposive and complementary assessment by resolving methodological inconsistencies and providing accurate terminology. In the long term, scarcity is most purposively addressed by focusing on depletion of ecospheric stocks. Accordingly, the Crustal Scarcity Indicator is proposed to assess potential long term

scarcity in life cycle assessment, alongside other environmental impacts. In the near term, potential scarcity for nations, industries and companies, as commonly assessed in criticality assessment, is most purposively addressed by focusing on technospheric circumstances, such as geopolitics, which can disrupt technospheric resource flows. In medium term, secondary resources in technospheric funds could be relevant, especially, with the advent of a more circular economy.

Altogether, it is recommended that implementation of RE measures to metal-diverse products are based on analysis of product characteristics and real-world conditions and that effects of RE measures are assessed by methodologies which distinguish between mineral resource flows, funds and stocks so that well-informed prioritizations between metals can be made.

KEYWORDS

scarce metals, life cycle assessment, area of protection - natural resources, criticality assessment, material flow analysis, supply risk, resource-efficiency, circular economy, electric and electronic equipment, complex products

LIST OF APPENDED PAPERS

This thesis is based on the work presented in the following appended papers:

I:
Böckin, D., Willskytt, S., André, H., Tillman, A.-M., & Ljunggren Söderman, M., 2020. How product characteristics can guide measures for resource efficiency — A synthesis of assessment studies. *Resources, Conservation and Recycling, 154*. doi:10.1016/j.resconrec.2019.104582

II:
Ljunggren Söderman, M., & André, H., 2019. Effects of circular measures on scarce metals in complex products – Case studies of electrical and electronic equipment. *Resources, Conservation and Recycling, 151*. doi:10.1016/j.resconrec.2019.104464

III:
André, H., Ljunggren Söderman, M., & Nordelöf, A., 2019. Resource and environmental impacts of using second-hand laptop computers: A case study of commercial reuse. *Waste Management, 88*, 268-279. doi:10.1016/j.wasman.2019.03.050

IV:
Arvidsson, R., Ljunggren Söderman, M., Sandén, B., Nordelöf, A., André, H., Tillman, A.-M., 2020. A crustal scarcity indicator for long-term global elemental resource assessment in LCA. The International Journal of Life Cycle Assessment 25, 1805-1817.10.1007/s11367-020-01781-1

V:
André, H., & Ljunggren, M., 2020. Towards complementary assessment of mineral resource flows, funds and stocks within the Area of Protection - Natural Resources. *manuscript submitted to a scientific journal.*

VI:
André, H., & Ljunggren, M., 2020. Supply disruption and depletion impacts in a company context: the case of a permanent magnet electric traction motor. *manuscript in preparation.*

CONTRIBUTIONS TO APPENDED PAPERS

I:

ML and AMT developed the idea and the research design. HA, DB and SW performed the data collection and investigation, formal analysis of synthesizing data, produced metadata and wrote the initial draft of the manuscript, in which HA wrote the introduction and aim, SW the method and DB the analysis, results and discussion and conclusions. All authors developed the methodology and the analytical framework, and critically reviewed and edited the manuscript. DB and AMT lead the revision of the manuscript to which HA, SW and ML contributed with critical review and editing.

II:

ML developed the idea and the research design. HA performed the data collection and investigation of the three case studies. HA performed the initial formal analysis of the three case studies and ML performed the formal analysis of additional scenarios (cradle to gate and changing material content). Both authors developed the methodology and ML the conceptualization of product complexity. HA led the writing of a conference paper on the study (André et al., 2016). ML led the writing and revision of the manuscript to which HA contributed with critical review and editing.

III:

HA and ML developed the idea and the research design. HA performed the data collection, investigation and the formal analysis, produced metadata, wrote the initial draft of the manuscript, revised the manuscript following peer-review comments, supervised by ML. All authors developed the methodology and critically reviewed and edited the manuscript.

IV:

All authors contributed to the conceptualization and methodology through reviewing the literature and engaging in a series of discussions spanning several years. RA led the work on data collection, investigation, formal analysis and writing, while ML, BS, AN, HA and AMT contributed in editing and revising manuscripts. HA specifically contributed to relating the study to the relevant literature on LCIA of mineral resources.

V:

Both authors developed the idea. HA developed the research design, performed investigation and the formal analysis of synthesizing data, produced metadata, developed the methodology and the analytical framework and wrote the manuscript, supervised by ML. Both authors critically reviewed and edited the manuscript.

VI:

Both authors developed the idea, research design and methodology and critically reviewed and edited the manuscript. HA performed the data collection, investigation, formal analysis and wrote the manuscript, supervised by ML.

OTHER PUBLICATIONS BY THE AUTHOR

Tillman, A.-M., Ljunggren Söderman, M., André, H., Böckin, D. and Willskytt S., 2020. Circular economy and its impact on use of natural resources and the environment - Chapter from the upcoming book Resource-Efficient and Effective Solutions – A handbook on how to develop and provide them. Report no. 2020:1. Chalmers University of Technology: Gothenburg, Sweden.

Tillman, A-M, Böckin, D., Willskytt, S., André, H. and Ljunggren Söderman, M, 2020. What Circular Economy Measures Fit What Kind of Product? Chapter in Handbook on the Circular Economy, M Brandão, D Lazaveric, G Finnveden (eds) forthcoming 2020, Edward Elgar Publishing Ltd.

André, H., and Ljunggren Söderman, M., 2019. Depletion and criticality as parts of comprehensive assessment of natural mineral resources? ISIE 2019, 10th International Conference on Industrial Ecology, Industrial Ecology for Eco-Civilization. July 7-11, Tsinghua University, Beijing, China.

André, H., 2018. Resource and environmental impacts of resource-efficiency measures applied to electronic products. Licentiate thesis. Gothenburg: Chalmers University of Technology, 2018.

André, H., Ljunggren Söderman, M., and Nordelöf, A., 2018. Effects on metal resource use from reusing laptops - A comparison of impact assessment methods. SETAC Europe 24th LCA Case Study Symposium, 24-26th September, Vienna, Austria.

André, H., Ljunggren Söderman, M., Tillman, A-M, 2016. Circular economy as a means to efficient use of scarce metals? Electronics goes green, September 7-9, 2016, Berlin, Germany. doi: 10.23919/EGG.2016.8396923

Willskytt, S., Böckin, D., André, H., Ljunggren Söderman, M. and Tillman, A-M., 2016. Framework for analysing resource-efficient and effective solutions. Eco-Balance 2016, October 3-6, Kyoto, Japan.

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LIST OF ABBREVIATIONS

AADP	anthropogenic extended abiotic depletion potential
ACS	automation control system
ADP	abiotic depletion potential
ADP-UR	abiotic depletion potential based on ultimate reserves
ADP-R&B	abiotic depletion potential based on reserves and reserve base
AoP	area of protection
AoP-NR	area of protection - natural resources
BAU	business as usual
CA	criticality assessment
CE	circular economy
CExD	cumulative exergy demand
CF	characterization factor
CSI	crustal scarcity indicator
EcoSc	eco-scarcity method
ELV	end of life vehicle
EPS	environmental priority strategies
EXT	use extension
IE	industrial ecology
LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment
LCI-UNEP	the life cycle initiative's task force on mineral resources hosted by the UN environment programme
LED	light-emitting diode
MFA	material flow analysis
RE	resource-efficiency
REE	rare earth element
PMSM	permanent magnet synchronous machine
PSS	product service systems
SOP	surplus ore potential
UR	ultimate reserves
URR	ultimately extractable resources
WEEE	waste electrical and electronic equipment

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CHAPTER 1 - Introduction

Natural resources such as metals are essential for products produced and demanded by humans, and, have been so from the bronze and iron ages to contemporary societies. As technology has developed, products have become increasingly complex. For instance, this is observable in terms of the diversity of metals used in products. The products of today use most metals of the periodic table (Greenfield and Graedel, 2013). When products reach their end-of-life however, only a few of the metals are functionally recycled at high rates, i.e. returned to material streams where their metal properties can be utilized again (Graedel et al., 2011; Guinée et al., 1999). Others may end up as impurities of recycled metals or dispersed in landfills or construction materials (Andersson et al., 2016; Reck and Graedel, 2012), and can thus be characterized as lost, at least for the time being. Moreover, many of today's products tend to have rather short lifetimes before being discarded. Thus, today's products require a metal-diverse, quite rapid, and to large extent linear throughput (Reck and Graedel, 2012). Concerns regarding the unsustainability of this linear throughput were raised already several decades ago (Boulding, 1966; Meadows et al., 1972). One concern regards the availability of natural resources, such as metals, in the ecosphere (i.e. the environment or natural systems) to be used as inputs to the economy, and thereby, the technosphere (i.e. man-made systems). Another concern regards the ecosphere's ability to act as a sink for the emissions of waste and pollution, i.e. the unwanted outputs from the economy.

Ideas for how to address such concerns have since then been formulated in various conceptual framings focusing on ways to extend the life of resources within the economy (Blomsma and Brennan, 2017) e.g. Cradle-to-cradle design (McDonough and Braungart, 2010) and the Performance Economy (Stahel, 2010). The circular economy (CE) can be described as an umbrella concept which incorporates such pre-existing conceptual framings around resource-life extension (Blomsma and Brennan, 2017). The aim of CE is to decouple the functions provided by products from their, to large extent, linear throughput and its associated environmental and resource impacts (Ghisellini et al., 2016; Kirchherr et al., 2017). In the CE discourse, measures to achieve resource-efficiency are often organized in "R-frameworks". These consist of resource-efficiency (RE) measures such as reduce, reuse, repair, and recycle with different granularity e.g. 3Rs, 4Rs, 6Rs and 9Rs. Moreover, most R-frameworks prioritize between measures, stating e.g. that it is more favourable to, in turn, reduce, reuse, repair, and, lastly, recycle (Kirchherr et al., 2017). While RE measures are generally expected to reduce resource and environmental impacts, the evidence is not plentiful (Blomsma and Brennan, 2017; Bocken et al., 2017; Korhonen et al., 2018). Plausibly, they could result in burden-shifting, i.e. reducing particular resource and environmental impacts at particular life cycle stages, but increase other impacts, at other life cycle stages. Making products more durable or repairable to extend their use may require other or more materials. Reusing and sharing products may reduce impacts from production but increase transportation. Therefore, it is acknowledged that there are exceptions where the priorities of R-frameworks suggest measures which are not favourable from an environmental life cycle perspective (European Commission, 2008). Furthermore, priorities of R-frameworks are based on ideal circumstances which cannot always be assumed when measures are implemented in the real world (Paper II). Real world implementations of CE may rather compose of "circular configurations" which combine several measures in sequence or in parallel (Blomsma and Brennan, 2017) (hereafter referred to as configurations of RE measures). Considering such exceptions to priorities of R-frameworks, there is a need for assessment studies from a life cycle perspective to provide more detailed guidance regarding under what circumstances RE measures actually are resource-efficient in terms of reducing resource and environmental impacts (Blomsma and Brennan, 2017; Haupt and Zschokke, 2017; Korhonen et al., 2018).

In terms of the effects of RE measures on the availability of mineral resources, such as metals, there is a variety of questions which can be assessed. Assessments can focus on used quantities of individual resources as such. They can also focus on assessing the contributions of using individual resources to potential scarcity, and, potential consequences of scarcity. In this thesis, all such assessments are referred to as addressing potential mineral resource scarcity impacts. This includes both concerns in the short term, such as supply disruptions, and in the long term, such as resource depletion.

Mineral resource scarcity is considered an environmental impact in LCA, related to the Area of Protection (AoP) of Natural Resources (AoP-NR). Other AoPs in LCA are ecosystem quality and human health (de Haes et al., 1999; Hauschild and Huijbregts, 2015). The AoP-NR implies that natural resource availability is to be safeguarded for potential use by humans (Berger et al., 2020; de Haes et al., 1999; de Haes et al., 2002; Jolliet et al., 2004). How to assess impacts on natural resource availability in LCA is however a long debated issue, especially for mineral resources (Steen, 2006). It has even been discussed whether or not impacts on natural resources ought to be assessed in LCA at all, since some argue that resource availability is an economic, rather than an environmental, issue (Drielsma et al., 2015). On the other hand, it has been argued that extraction of resources from the ecosphere naturally changes the resource availability in the ecosphere, which reasonably should be considered an environmental issue (Sonderegger et al., 2017).

In addition to the discussion on whether or not to assess impacts on mineral resource availability in LCA, there have been much discussion on *how* to assess it. Such discussions have concerned (Berger et al., 2020; Klinglmair et al., 2014b; Schulze et al., 2020a; Steen, 2006):

- the *safeguard subject*, i.e. what, more precisely, about resources is to be safeguarded under the AoP-NR and for which stakeholder or user?

- what the associated *problem* which threatens the safeguard subject is. For instance, both physical geological rarity and extraction costs (either in monetary or energy terms) can be considered relevant constraints to resource availability for future generations. Respectively, these constraints make depletion of geological availability and increased future extraction costs relevant problems to assess.

- what modelling concepts and practical implementations best reflect the safeguard subject and problem formulations. For instance, if depletion of geological availability is considered the relevant problem one may relate mineral resource use to estimates of geological availability using factors such as reserves or crustal content. Or, if increased future extraction costs are considered the relevant problem, one may relate the contributions of resource extractions today, to estimates of how much more costly resource extractions will be in the future, assuming that extraction costs depend on ore grades and that higher ore grades are less costly to extract from, and extracted first.

In this thesis, the combination of safeguard subject, problem, modelling concept and practical implementation is referred to as a *principle of prioritization.* This is used as an umbrella term for characterization of mineral resources in resource assessment methods. This term will be further explained in section 2.4. Mineral resource impact assessment methods in LCA (LCIA-methods) which are used to characterize the relative contributions of resources to a potential impact are based on a variety of such principles of prioritization which are known to give largely diverging results (see e.g. (Finnveden et al., 2016; Peters and Weil, 2016; Rørbech et al., 2014)).

In addition to the constraints which are commonly assessed in LCA, it has been pointed out that, for instance, geopolitical and socio-economic issues, may cause supply disruptions and thereby constrain resource availability for humans (Dewulf et al., 2015; Finnveden, 2005). It has therefore been argued that potential supply disruption and impacts thereof (hereafter collectively referred to as supply disruption impacts), could also be relevant to consider in the AoP-NR (Dewulf et al., 2015; Mancini et al., 2013; Sonnemann et al., 2015). It is not clear, however, whether assessments of supply disruption impacts are to be considered part of LCA or as complementary assessments in e.g. life cycle sustainability assessment (LCSA) (Berger et al., 2020) or criticality assessment (CA) (Dewulf et al., 2015). Nonetheless, regardless in which methodology it takes place, assessment of supply disruption impacts add yet more principles of prioritization to the variety already existing in LCIA. Much like for LCIA-methods, there is a variety of principles of prioritization used by numerous methods which give diverging results (Dewulf et al., 2016; Graedel and Reck, 2016; Schrijvers et al., 2020).

The diversity of principles of prioritization in resource assessment methods which can be used to address different safeguard subjects related to the AoP-NR (Cimprich et al., 2019; Dewulf et al.,

2015) seems to bring about confusion. For example, this is visible in interchangable or ambiguous uses of terms such as “scarcity”, “criticality” and “depletion” in the scientific literature (Paper V) and practitioners mistakenly using methods assessing depletion impacts although they are interested in assessing supply disruption impacts (Berger et al., 2020). Such terminological and methodological ambiguity suggests that there is a great need to clarify the similarities and differences between principles of prioritization in resource assessment methods as such. Furthermore, such clarification is essential for drawing conclusions regarding when, and based on what principles of prioritization, products can be considered resource-efficient, i.e. reducing mineral resource scarcity, as intended within the CE vision.

1.2 Aims and research questions

The overall aim of this thesis is to build knowledge on the effects of RE measures on mineral resource scarcity and on methodological considerations in assessing such effects. Contributions towards this aim are made through addressing the following research questions (RQs):

RQ1: How do RE measures applied to metal-diverse products affect mineral resource scarcity from a life cycle perspective?

RQ2: What are the similarities and differences between principles of prioritization between metals in mineral resource assessment methods?

This RQ can be divided into two subquestions:
RQ2.1: What are the similarities and differences between principles of prioritization assessing potential depletion and supply disruption impacts?
RQ2.2: What are the similarities and differences among LCIA-methods assessing potential depletion impacts?

The third and final research question draws on insights from the first and second research questions and is formulated as follows:

RQ3: How may principles of prioritization between metals in mineral resource assessment methods affect conclusions regarding prioritizations between metals when applying RE measures to metal-diverse products?

1.3 Structure of thesis

Chapter 2 outlines some background on main research gaps addressed and assessment methods used, including both some historical roots and more recent state of the art knowledge. Chapter 3 outlines the research design and methodology. Chapter 4 summarizes the main contributions from the appended papers to the research questions. Chapter 5 compares the main findings to literature and discusses implications for industry, policy and future research. Chapter 6 summarizes the conclusions and provides some recommendations.

CHAPTER 2 - Background

2.1 Scarcity of mineral resources

The term ”scarce” is defined as ”deficient in quantity or number compared with the demand” (Merriam-Webster, n.d.). In other words, scarcity is an economic concept denoting a situation where demand exceeds supply. When it comes to scarcity of *natural resources*, defined as “material and non-material assets occurring in nature that are at some point in time deemed useful for humans” (Sonderegger et al., 2017), we are thus dealing with a concept which is inherently both economic and environmental. The definition of scarce can be contrasted with the definition of “rare” which is “seldom occurring or found” (Merriam-Webster, n.d.).

As a result of the duality which is inherent to the concept of natural resource scarcity, economic and environmental scholars have debated questions concerning natural resource scarcity from different perspectives, e.g. in the limits to growth debate (Jackson and Webster, 2017; Meadows et al., 1972; Solow, 1974). Regarding non-renewable resources in particular, such as mineral resources, two opposing perspectives in such debates are referred to as the “fixed stock” and “opportunity cost paradigms” (Tilton, 1996). Proponents of the fixed stock perspective view the Earth as a materially closed system in which mineral resources may be depleted from forms in which they are available to humans e.g. due to extraction from nature into the economy (Daly, 1992). Thus, continued extraction is regarded to potentially make mineral resources scarce for future generations. Proponents of the opportunity cost perspective refer to mineral resources as abundant in the Earth’s crust and, accordingly, rather focus on the costs of extraction (Tilton, 1996). Generally, the more easily minable deposits tend to be mined first and deposits requiring more effort later. Consequently, extraction costs tend to increase as a result of continuous extraction. However, higher extraction costs will also increase the prices and thereby limit demand. Thus, what is regarded to limit the availability of mineral resources is the opportunity cost i.e. what else society is willing to give up to extract mineral resources (Tilton, 1996).

2.2 A circular economy of metals?

The concept of a “Spaceship economy ” Boulding (1966) is one of the key theoretical foundations of the CE vision. Two metaphors are used to describe the relation between material resources, waste and economies. These metaphors largely embody the fixed stock and opportunity cost perspectives. The predominant pattern of the industrial economy is likened to a “cowboy economy” where resources and waste sinks are perceived as abundant in relation to the economy. In a cowboy economy, there are always more resources and waste sinks available beyond the horizon. Analogous to the opportunity cost perspective, the question is merely the distance one is willing to go to acquire additional resources. Thus, the resource throughput can be predominantly linear. However, Boulding argued that a spaceship is a more accurate metaphor for describing the relations between material resources, waste sinks and the economy. In a "Spaceship economy", natural resources are scarce in relation to the economy. There is no horizon beyond which new resources can be discovered, so the finite resources available need to be continuously recirculated.

Georgescu-Roegen (1986) suggested that the economy fundamentally depends on the input of natural resources, both energy and materials, and the emission of low grade (high entropy) energy and dispersed materials, such as metals, as wastes. However, the economy does not necessarily disperse metals (Ayres, 1999; Kåberger and Månsson, 2001; Korhonen et al., 2018). This can be seen in the case of landfills which sometimes have higher metal concentrations than primary ores (i.e. leaving the economy in lower entropy than when entering) (Kåberger and Månsson, 2001). In theory, metals can be infinitely recycled provided that enough solar energy, which is instantly renewed and infinite, can be harnessed by the technosphere (Ayres, 1999; Kåberger and Månsson, 2001; Korhonen et al., 2018).

Nevertheless, once metals have been dispersed, searching, collecting and recycling metals is very costly (Daly, 1992; Korhonen et al., 2018) e.g. in energetic and monetary terms, depending of course, on the degree of dispersion. In other words, the opportunity cost of recycling dispersed metals is high. As is evident from global metal recycling rates (Graedel et al., 2011) it currently discourages the recycling of most metals. Therefore, even though metals can, in theory, be infinitely recycled, it is sensible to avoid unnecessary dispersion by means of RE measures proposed within the CE discourse (Korhonen et al., 2018). Effectively, this means prolonging the use of metals within the technosphere today rather than leaving the onerous and costly work of searching, collecting and recycling dispersed metals to future generations.

2.3 Systems science and industrial ecology

Achieving a more circular economy of metals could potentially be favourable from many points of view: as a means for reducing environmental impacts from metal life cycles (UNEP, 2013), potential depletion (Korhonen et al., 2018), probability of supply disruption and criticality (by being less dependent on primary extraction) (Tercero Espinoza et al., 2020). Thus, there are several reasons for examining the effects of RE measures on mineral resource scarcity impacts. As a result, there are also several methodologies which can be used. The effects on metal flows as such can be studied by means of material flow analysis (MFA) (Brunner and Rechberger, 2004). The effects on environmental impacts, including mineral resource depletion, can be studied by means of LCA (ISO, 2006). The effects on supply disruption probability and criticality can be studied by means of CA. Alternatively, such supply disruption impacts can be assessed by a means of a fairly new type of methods which aim to reflect criticality within LCA methodology. These methods are in this thesis called hybrid methods of CA and LCA, or simply hybrids.

These methodologies are rooted in the field of Industrial Ecology (IE). IE is an interdisciplinary systems science which can be defined as "*the study of technological organisms, their use of resources, their potential environmental impacts, and the ways in which their interactions with the natural world could be restructured to enable global sustainability."* (Graedel and Allenby, 2010).

Systems science, in turn, is characterized by the aim to solve real-world problems by means of modelling complex phenomena in terms of components and their interrelations which together form a system (Churchman, 1967). Another characteristic of systems science is that it has to be interdisciplinary in order to solve the problems it aims to solve "attempting scientific interpretation and theory where previously there was none" (Von Bertalanffy, 1968). Systems theory can be understood as a form of "skeleton" which holds the disciplines together (Boulding, 1956) or a way of thinking about, modelling, understanding and describing real-world phenomena pertaining to various disciplines in general terms (Churchman, 1967). Systems science can be understood as the application of systems theory. It follows that theories are commonly borrowed between disciplines. In particular, there is a strong tradition within system sciences to borrow from biology, i.e. the study of natural systems, when theorizing around man-made systems such as social and technological ones (Ingelstam, 2012; Von Bertalanffy, 1968). For example, IE is based on an analogy between natural and technical systems, as implied e.g. by referring to a technological entity as a "technological organism" (Graedel and Allenby, 2010).

2.3.1 Material flow analysis (MFA)

MFA is a methodology used to quantify material flows and, sometimes stock accumulation, in a specified system. MFA studies may focus on e.g. global, national, process or product system levels. They may focus on aggregated material flows such as products or alternatively a number of substances (also referred to as substance flow analysis). A material flow system model is based on mass balance of inputs and outputs over each process and corresponding transfer coefficients. The results of MFAs are typically presented in the form of Sankey diagrams where thickness and direction of arrows represent magnitudes and direction of material flows (Brunner and Rechberger, 2004). Using MFA can be conducive to identifying material flow patterns, and thereby, to support decision-making regarding material use or substances of concern (Bringezu and Moriguchi, 2002). For instance, they can provide guidance in efforts to dematerialize studied systems to achieve resource-efficiency (by minimizing inputs and outputs in relation to a specific *desired* output) or to minimize potentially hazardous emissions of e.g. toxic materials (Bringezu and Moriguchi, 2002).

2.3.2 Life cycle assessment (LCA)

LCA is a methodology used to systematically quantify all relevant environmental impacts of a product, over the course of its life cycle, i.e. "from cradle to grave". It consists of four phases: goal and scope definition, inventory analysis, impact assessment, and continuous interpretation.

The goal and scope definition phase determines: the purpose of the LCA; the functional unit (a measure of function performed by a product to which environmental impacts are related so that e.g. different products providing the same function can be compared); environmental impact categories and system boundaries e.g. geographical, temporal, life cycle phases.

In the life cycle inventory (LCI) analysis phase, a model is constructed of the technical system, consisting of the studied product as well processes along its life cycle (e.g. extraction and production, use and disposal (post-use), referred to as the product system (ISO, 2006). Further, environmentally relevant input and outputs, i.e. flows of resources and emissions of each process within the product system are established. The final life cycle inventory is the result of quantifying all flows from and to the ecosphere attributed to the functional unit. These flows are referred to as elementary flows. (Baumann and Tillman, 2004)

In the life cycle impact assessment (LCIA) phase, the LCI is translated into potential environmental impacts. The system boundary between technosphere and ecosphere thus separates LCI (modelling technosphere) from LCIA (modelling impacts in the ecosphere). This translation is achieved by multiplying elementary flows with characterization factors (CFs) which reflect the relative significance of elementary flows for specific environmental impact categories. CFs are derived by modelling cause-effect chains through steps such as fate, exposure, effect and damage (Hauschild et al., 2018). Typically, the modelling of cause-effect chains becomes more complex the longer they are. A distinction is therefore made between two types of indicators: midpoint and endpoint. Endpoint indicators model impacts close to or until the AoP, i.e. human health, ecosystem quality or natural resources. Because they model more complex cause-effect chains than midpoint indicators they are often argued to be more relevant but also more uncertain (Bare et al., 2000).

2.3.3. Criticality assessment (CA)

CA is a methodology used to assess probability of supply disruption and vulnerability to supply disruption for a stakeholder within a time frame (Schrijvers et al., 2020). Because contemporary societies are highly dependent on metal-diverse technologies and products, and hence, vulnerable to metal supply disruptions, CA has gained widespread interest in the 21st century (Erdmann and Graedel, 2011; Graedel and Reck, 2016). CA can be performed on several system or stakeholder levels ranging from global humanity, supra-national and national economies, industry sectors or technologies to companies (Schrijvers et al., 2020).

Phenomena related to criticality, for instance, dependence on foreign mineral resources, date back as early as the bronze age (Buijs et al., 2012). CA and the term “critical and strategic material” have been used in the context of US defense policy since the beginning of the second world war (NRC, 2008). As an academic field however, CA is still quite young. It emerged after the US National Resource Council’s publication (NRC, 2008) of critical materials for the US economy. Since then, a vast number of CA methods and studies have been published originating from, primarily, academia and governments.

Most CA methods consist of two axes: probability of supply disruption and vulnerability to supply disruption (Dewulf et al., 2016). Common factors reflecting the former are, for instance, concentration of production or reserves, political stability, depletion time of reserves (Achzet and Helbig, 2013). Common factors reflecting the latter are substitutability and value of products affected by a supply disruption (Helbig et al., 2016). Hence, the rationale of most CA methods is that if resources are concentrated in a few countries there is a higher probability of supply disruption, especially, if those countries are e.g. politically unstable. And, if resources are difficult to substitute and used in valuable or strategic products or technologies, there is a higher vulnerability to supply disruption.

There are however large differences between methods in terms of methodological choices and the results they produce. Considering that “criticality is in the eye of the beholder” meaning that it reflects the conditions of a specific stakeholder (Eggert, 2011) it is not surprising that results vary. And, considering that methodological concepts and practical implementations need to be aligned with the problem perceptions that are relevant at the different system levels or to different individual stakeholders it is not surprising that there is plenty of methodological differences among CA methods. But this can only explain some of the differences (Schrijvers et al., 2020). It has been pointed out that there is a lack of justification with regard to methodological choices (Frenzel et al., 2017) and, consequently, misalignments between problem formulations, modelling concepts and practical implementations. For such reasons, it has been pointed out by several authors that some harmonization efforts would be beneficial (Dewulf et al., 2016; Graedel and Reck, 2016; Schrijvers et al., 2020).

2.4 Principles of prioritization between metals

The methodologies described in this chapter and the specific methods pertaining to them are in this thesis analysed using a simplified version of the framework developed by Schulze et al. (2020a) It consists of the following aspects which are explained and exemplified in Table 1: safeguard subject, problem, modelling concept and practical implementation. The sum of these aspects is referred to as a *principle of prioritization*, simply because they together result in a ranking between mineral resources. In other words, principles of prioritization are the underlying reasons for the prioritizations of resource assessment methods, such as CFs in LCA and hybrid methods, and, criticality scores in CA. Ideally, the safeguard subject, i.e. what is to be protected, is aligned with the problem formulation, i.e. what prevents the safeguard subject from being protected and, in turn, with the modelling concept and the practical implementation. However, it is not uncommon that safeguard subjects and problem formulations are not aligned with modelling concepts and/or practical implementations. This has been demonstrated both for LCIA-methods (Drielsma et al., 2015; Schulze et al., 2020b) and CA methods (Schrijvers et al., 2020). In this thesis and in Paper V, such misalignments are referred to as misalignment between *intended* and *actual scopes*. In other words, safeguard subject and problem formulation are collectively referred to as *intended scope* whereas modelling concept and practical implementation are collectively referred to as *actual scope*.

For simplicity, the term "method" and some aspect of it will predominantly be used henceforth to refer to the principle of prioritization of methods. For instance, "reserve-based methods" or "methods based on average crustal concentrations" is used to refer to methods which have chosen particular types of factors in their practical implementations.

Table 1. Simplified framework for analysis of resource assessment methods adapted from (Schulze et al., 2020a). A principle of prioritization is defined as the sum of a resource assessment method's safeguard subject, problem, modelling concept and practical implementation.

Safeguard subject *- What is to be protected?*	*Problem* *- What prevents the safeguard subject from being protected?*	*Modelling concept* *- What is the basis for impact assessment?* E.g. mass, energy content or different types of costs	*Practical implementation* E.g. equations for CF, indicators, factors, data
Example: Mineral resource availability for future generations	Example: Depletion caused by current mineral resource use	Example: Relation of current use to ultimately available mineral resources	Example: Reserve base as estimate of ultimately available mineral resources
Intended scope		Actual scope	

Natural resources have been described as "sandwiched in" between the ecosphere and the technosphere (Dewulf et al., 2015). This inherent duality of the concept of natural resource scarcity, being both economic and environmental, has called for a more comprehensive assessment of the AoP-NR than one solely assessed by LCA (Mancini et al., 2013; Sonnemann et al., 2015). Berger et al. (2020) define the safeguard subject for mineral resources within the AoP-NR as *"the potential to make use of the value that mineral resources can hold for humans in the technosphere".* This definition seems to be broad enough to include the scopes of LCIA methods as well as CA and hybrid methods. Resource assessment methods within LCA, MFA, CA and hybrids deploy a diversity of principles of prioritization, which will here be briefly introduced.

2.4.1 Life cycle impact assessment (LCIA)

LCIA methods have over the years been categorized in slightly different ways (Klinglmair et al., 2014b; Sonderegger et al., 2017; Steen, 2006). Most recently, the Life Cycle Initiative's task force on mineral resources, hosted by the UN Environment Programme (LCI-UNEP) categorized four method types: depletion, future efforts, thermodynamic accounting and supply risk (Sonderegger et al., 2020). The first three of these characterize individual mineral resources with the intention to safeguard future availability of mineral resources but with different problem formulations and modelling concepts.

Supply risk methods characterize individual mineral resources to an entirely different safeguard subject, namely availability of mineral resources for a studied product system. Because of this, there is a crucial distinction between supply risk methods and the other method types, namely the directionality of impacts in relation to the studied product system. Normally, LCA assesses impacts caused by product systems on the environment. This is referred to as inside-out impacts. Conversely, supply risk methods assess potential impacts from within the technosphere on the studied product system. This is referred to as outside-in impacts.

Because of this difference, there was no consensus in the LCI-UNEP on whether supply risk methods are to be considered part of LCA or not (Berger et al., 2020). Hence, in this thesis they are referred to as hybrid methods (of CA and LCA) since referring to them as supply risk type LCIA-methods could be controversial. They are also included in a review of CA methods (Schrijvers et al., 2020) which further supports the choice not to categorize them as neither pertaining to LCA nor CA but as hybrids thereof.

The introduction of CA and hybrids to the AoP-NR, add yet more principles of prioritization to choose from. While a more comprehensive assessment of the AoP-NR (than one only addressed by LCA) may be a step in the right direction towards better decision-making, it may also add even more confusion in a field of already ambiguous methodologies and prevalent misinterpretations. Central concepts such as “criticality”, “scarcity” and “depletion” are commonly used interchangably or ambiguously in the scientific literature. Further, it happens that industry practitioners mistakenly use LCIA-methods assessing depletion although potential supply disruption is what they really are interested in (Berger et al., 2020). In addition, some methods seem to mix up supply disruption and depletion impacts (see e.g. Global Resource Indicator (Adibi et al., 2017). Such terminological and methodological ambiguity and the suggested potential for a comprehensive assessment of mineral resource scarcity called for comparing and analysing principles of prioritizations within LCIA, CA and hybrids collectively (Paper V). Other works have focused on either LCIA methods and hybrids (Berger et al., 2020; Sonderegger et al., 2020) or CA methods and hybrids (Schrijvers et al., 2020) but did not compare LCIA, CA and hybrids collectively using a common framework.

2.4.2 Criticality assessment (CA)

CA can be defined as *“the field of study that evaluates the economic and technical dependency on a certain material, as well as the probability of supply disruptions, for a defined stakeholder group within a certain time frame”* (Schrijvers et al., 2020). In other words, the instrumental value of resources for producing products and generating economic revenue or wealth for a given stakeholder is itself, the safeguard subject. Consequently, there is essentially an infinite number of safeguard subjects and, hence, principles of prioritization based on criticality. Accordingly, CA methods differ significantly from each other in terms of problem (referred to as “anticipated risk” (Schrijvers et al., 2020)) e.g.

shutdown of production, modelling concept (e.g. one, two or three dimensional) (Dewulf et al., 2016; Graedel and Reck, 2016)) and practical implementation (e.g. which factors are included) (Achzet and Helbig, 2013; Helbig et al., 2016; Schrijvers et al., 2020).

Schrijvers et al. (2020) points out that there is misalignment between problems and choice of factors in many CA methods. To contribute to better alignment, Schrijvers et al. (2020) suggest to analyse CA in terms of cause-effect chains. This research gap, of analysing criticality in terms of cause-effect chains, was addressed in Paper V but not primarily for the purpose suggested by Schrijvers et al. (2020) (but it can provide some ground for such work). Rather, the purpose was to compare CA as a methodology with LCIA and hybrids. Ultimately, this aimed to explicate if and how the methodologies could complement each other in a more comprehensive assessment of the AoP-NR.

2.4.3 Material Flow Analysis (MFA)

In MFA, there is no characterization of individual materials to a common question, such as mineral resource scarcity as in LCIA, CA and hybrids. Instead, common indicators based on MFA focus on quantities of materials as such (Bringezu and Moriguchi, 2002). Nonetheless, the choice of materials or substances to study may very well depart from a specific predefined concern such as potential toxic emissions or mineral resource scarcity. Moreover, it can be argued that the principle of prioritization is that use of each specific metal constitutes a unique problem. This reflects that metals often have unique properties and cannot be substituted for one another. In any case, the principle of prioritization of MFA has the benefit of producing easily interpreted results which can be discussed in relation to several safeguard subjects. In Paper II, this allowed for discussing both disruption and depletion impacts.

2.5 State-of-the-art knowledge on effects of RE measures on mineral resource scarcity

In Paper I, a literature review was conducted of comparative assessment studies of RE measures applied to a wide variety of product types from several sectors. A typology of RE measures from a life cycle perspective was created to support the analysis consisting of four principal categories (Figure 1): measures in extraction and production; measures in the use phase, in turn, divided into measures which aim to *minimize impacts from the use phase* and measures which aim *to extend the use phase*; and, lastly, measures post use.

In particular, the study focused on measures in the use phase. It became clear that few assessment studies of measures in the use phase had an explicit focus on mineral resource scarcity. Hence, Paper I did not focus much on mineral resource scarcity in particular. Nonetheless, it was useful as an overview of comparative assessment studies of RE measures applied to metal-diverse products. As such, it provided some overarching insights on effects of RE measures on mineral resource scarcity and helped to identify research gaps.

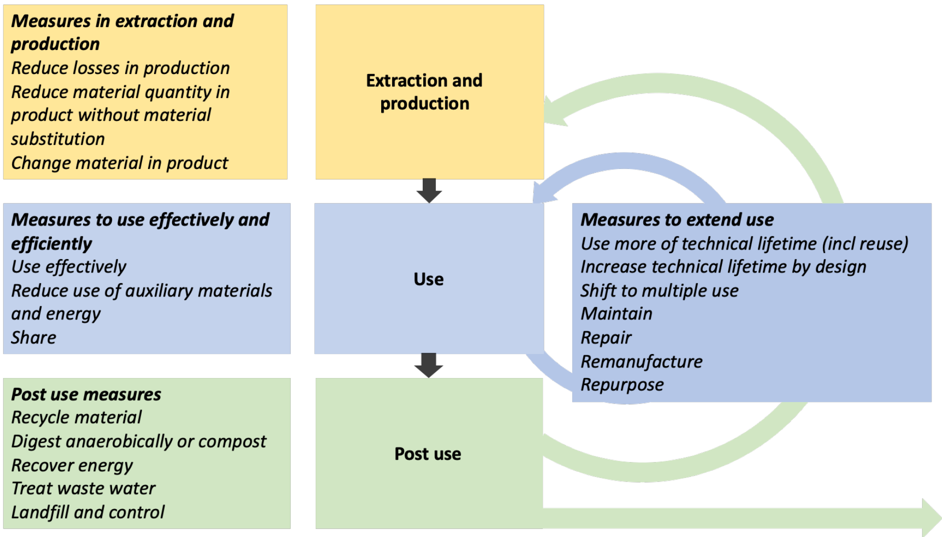

Figure 1. A typology of RE measures from a life cycle perspective (Paper I).

It was observed that impacts on mineral resource scarcity often increase due to efforts to decrease environmental impacts, e.g. through RE measures such as *reduce use of auxiliary materials and energy* and *increase technical lifetime*. Reducing the use of fossil fuels by replacing internal combustion engine cars with plug-in hybrids increases mineral resource scarcity (both potential supply disruption and depletion impacts) (Henßler et al., 2016). Similarly, lightweighting of vehicle doors (Soo et al., 2016) or engines (Böckin and Tillman, 2019) may require an increased material complexity, and thus, reduce climate change impacts at the cost of increased mineral resource depletion impacts. Another example is the use of sensors in waste bins to optimize waste collection (Bonvoisin et al., 2014).

Likewise, increasing the technical lifetime of products can reduce environmental impacts at the cost of resource depletion impacts. For instance, a more durable refrigerator may require more copper (Iraldo et al., 2017) and a modular smartphone more gold (Proske et al., 2016). This pattern is also observable in the case of substituting cobalt in lithium-ion batteries (Reuter, 2016). Substituting cobalt can reduce both potential supply disruption and depletion impacts but it also decreases the energy density of the battery, thus, shifting burdens to other environmental impacts (Reuter, 2016). In this regard, it was observed that mineral resources such as metals often have specific properties which makes it difficult to draw general conclusions regarding conditions for e.g. favourable substitution.

Altogether, it is possible to discern from these life cycle-based studies that material complexity, and consequently, increased mineral resource scarcity, is often a result of attempting to reduce other environmental impacts, such as climate change. Except for this pattern of increased mineral resource scarcity, it was not possible to draw further conclusions about the effects of RE measures on mineral resource scarcity because it was not in sufficient focus in the assessment studies.

Thus, Paper 1 confirmed that, prior to this thesis, there was limited knowledge regarding effects of RE measures on mineral resource scarcity, in particular, regarding the impacts on multiple metals. Comparative assessment studies of RE measures applied to metal-diverse products such as laptops largely focused on the trade-off between use extension and energy efficiency (Bakker et al., 2014; Quariguasi-Frota-Neto and Bloemhof, 2012; Sahni et al., 2010; Schischke et al., 2003; Williams and Sasaki, 2003). Moreover, most were based on “desktop-research” or idealized cases, thereby, potentially overlooking important aspects of RE measures as implemented in practice. For instance, comparative assessment studies of RE measures applied to smartphones assumed that all modular smartphones are repaired (Güvendik, 2014) or collected for recycling (Proske et al., 2016), thereby, disregarding potential losses to other pathways over the course of their life cycles. It has been stressed that case studies examining the effects of real-world configurations of RE measures could make valuable contributions to theoretical and practical knowledge within the CE discourse (Blomsma and Brennan, 2017; Geissdoerfer et al., 2017; Korhonen et al., 2018).

In addition, the few assessment studies synthesized in Paper I which did include mineral resource scarcity impacts seldom discussed the potential influence of the resource assessment methods in relation to the results. Resource assessment methods in LCA are known to give diverging results (see e.g. (Finnveden et al., 2016; Peters and Weil, 2016; Rorbech et al., 2014)). Hence, it is plausible that they could influence the effects of RE measures in terms of mineral resource scarcity. This motivated RQ3 and the choice to study impacts from RE measures on mineral resource scarcity using MFA in Paper II and several LCIA-methods in Paper III.

CHAPTER 3 - Research design and methodology

The research questions of this thesis differ in nature and consequently require different research approaches. RQ1 is the most empirically oriented, RQ2 the most theoretically oriented, and, RQ3 draws on insights from both RQ1 and RQ2. The contributions to the RQs have been made by means of case study research, synthesis of literature and method development. An overview of the appended papers, type of impacts assessed, analytical methods and assessment methods is presented in Table 2.

Table 2. Overview of research questions, types of impacts studied, analytical methods and assessment methodologies and appended papers.

Research question	*Type of Impact*	*Methods*	*Paper*
RQ1: How do RE measures applied to metal-diverse products affect mineral resource scarcity from a life cycle perspective?	Environmental and resource impacts, including mineral resource scarcity	- Synthesis of assessment studies in the scientific literature based on LCA, MFA, hybrid of CA and LCA - Case studies based on MFA and LCA	- PI - PII, PIII
RQ2: What are the similarities and differences between principles of prioritization between metals in mineral resource assessment methods?	Mineral resource scarcity (depletion and criticality)	- Method development within LCA - Synthesis of review studies on methodology within LCA, CA and hybrids of LCA and CA	- PIV - PV
RQ3: How may principles of prioritization between metals in mineral resource assessment methods affect conclusions regarding prioritizations between metals when applying RE measures to metal-diverse products?	Mineral resource scarcity (metal use, depletion and criticality)	- Case studies based on MFA, LCA, CA and hybrids of LCA and CA.	- PII, PIII, PVI

3.1 Research context

The work presented within this thesis has been conducted within the Mistra REES (Resource Efficient and Effective Solutions) research program. This research program studies the interrelations between policy, design and business models for supporting the Swedish manufacturing industry in transitioning towards a more resource-efficient and circular economy. The role of the research group at Chalmers University has been to study resource and environmental impacts of RE measures. A substantial part of the work behind this thesis has consisted of collaboration with companies within the research program. This has enabled carrying out case studies based on real-world business cases.

3.2 Case study research

Case study research is an empirical form of scientific inquiry where phenomena are examined in their real-world context (Yin, 1981). Their proximity to real-world contexts make them conducive to describing real-world phenomena (Flyvbjerg, 2006). On the other hand, their proximity to real-world contexts can raise concerns that they merely produce context-dependent knowledge of limited generalizability. Flyvbjerg (2006) however argues that rather than statistical generalization, case studies allow for generalization based on analysis and in-depth understanding of studied phenomena. In fact, they may be the ideal form of inquiry for falsification, since merely one case study may be enough to falsify a theory (Flyvbjerg, 2006).

The activities of companies within the research program have largely constituted the real-world configurations of RE measures which have been studied by means of case study research (Papers II and III). Empirical data required for modelling the product systems representing these RE configurations have largely been collected by means of interviews and site visits at companies. Examples of such empirical data are information about sourcing and sale of products, typical product lifetimes, business models, information about customer segments (e.g. quality requirements and geographical scope), component replacement rates, fates of products or components whose use cannot be extended etc.

The case study presented in Paper VI aimed to apply a research approach and a newly developed method born out of the theoretical and methodological work behind Papers IV and V. This theoretical and methodological background fit with arising questions from one of the companies within the research program, who were interested in learning more about mineral resource scarcity and different resource assessment methods.

3.3 Synthesis of literature

While case studies as such can provide depth, synthesis of a larger sample of case studies can provide breadth (Flyvbjerg, 2006). Consequently, conducting case studies and synthesizing knowledge from various case studies are two forms of scientific inquiry which may complement each other and are both essential for producing scientific knowledge (Flyvbjerg, 2006). Synthesizing literature can however be challenging if the methods and data used by synthesized studies are not transparent (Flyvbjerg, 2006).

In the synthesis of assessment studies in the life-cycle based literature (Paper I) it was crucial to understand how method and data used in the assessment studies influenced the results. Transparency was thus a selection criteria and key assumptions, data and methods were extracted and noted along with the results.

In Paper V, a synthesis was conducted of reviews of LCIA, CA and hybrids. The purpose of synthesizing review studies was to gain a deeper understanding of the similarities and differences between methodologies and potentially make some clarifications. As explained by Merton (1967): *"a good part of the work called theorizing is taken up by the clarification of concepts, and rightfully so."* Being a qualitative study, it was crucial to be transparent about how conclusions were substantiated by claims in the synthesized studies. Accordingly, direct quotes substantiating each claim were presented at length in the supplementary material.

3.4 Method development

Departing from the observation that there was a need for, and lack of, an LCIA-method for assessing mineral resource scarcity impacts in a long term perspective, a group at the division of Environmental Systems Analysis (the division where this thesis has been written) set out to develop such a method. The development of this method, the Crustal Scarcity Indicator (CSI), is presented in Paper IV.

The CSI was compared both quantitatively and qualitatively with a selection of other LCIA-methods. The quantitative comparison allowed for identifying similarities and differences in the prioritizations, i.e. CFs of the methods, and discussing the underlying reasons, i.e. their principles of prioritization. The qualitative comparison focused on three criteria: temporal reliability, methodological coherence and practical applicability. These criteria were chosen to be able to conclude whether the developed method actually was a more purposive LCIA-method for assessing impacts on long term mineral resource scarcity. Temporal reliability means that CFs are stable over time, which is particularly important in the case of long-term impacts to avoid fluctuating assessments. To illustrate, resources with the highest prioritization (i.e. CF) at present, ought to reasonably have the highest prioritization in ten years from now as well, especially, if the assessments are to provide guidance with regard to long term impacts e.g. more than a hundred years from now. Methodological coherence means that CFs are calculated the same way, i.e. there are no or few anomalies in the practical implementation. Practical applicability refers to breadth of scope of the method, in this case, the number of resources characterized.

CHAPTER 4 - Results

4.1 Effects of RE measures on mineral resource scarcity

This section accounts for the contributions to RQ1: how do RE measures applied to metal-diverse products affect mineral resource scarcity from a life cycle perspective?

Paper I

The first steps in addressing RQ1 were taken through the research behind Paper I, a synthesis of life cycle-based assessment studies. As explained in Chapter 2, Paper I did not focus on mineral resource scarcity in particular since this was not in sufficient focus in the synthesized assessment studies. Nonetheless, in addition to the overarching insights and the research gaps accounted for in Chapter 2, Paper I contributes to addressing RQ1 by providing knowledge on how the effects of RE measures on resource and environmental impacts, including mineral resource scarcity, generally depend on product characteristics and potential trade-offs of each RE measure.

The synthesis of life-cycle based assessment studies in the literature reveals that key product characteristics decisive for the effects of RE measures are: whether products are durable or consumable, active or passive, used for their full technical lifetime, used frequently and their pace of development. Since metal-diverse products are predominantly durable products, only the findings related to durable products are discussed here. Further, product complexity is discussed as a potentially decisive characteristic in both the assessment studies and in the literature which inspired the development of the analytical framework of Paper I, e.g. eco-design literature (Ceschin and Gaziulusoy, 2016). However, the assessment studies synthesized in Paper I do not allow for drawing conclusions about the influence of product complexity. Instead, this was identified as a research gap which was addressed as part of the analysis in Paper II.

The assessment studies largely focused on how impacts from durable products can be reduced through more efficient and effective use or by use extension. For durable products, the pace of development of newer products can be decisive for impacts. Products with a rapid pace of development in terms of e.g. functionality, energy efficiency or fashion tend to be discarded before they reach their full technical lifetimes. Impacts from such products can be reduced through reuse by another user. And, if they are infrequently used, their impacts can be reduced through sharing, as this can enable them to provide more functionality before being considered obsolete and discarded. However, sharing does not reduce impacts of products that are discarded sooner because of use and that tend to be used for their full technical lifetimes. For example, car sharing does not reduce impacts unless the person distance travelled per car increases. In addition, rebound effects need to be avoided. In other words, distance travelled per person must not increase. Further, impact reduction from sharing products may also be offset if fossil-fuel based transportation is required for users to access the shared products, as seen in assessment studies on sharing of tools (Mont, 2004) and clothes (Roos et al., 2015).

In addition to these product characteristics, an important system-level characteristic decisive for the effects of RE measures is what life cycle phase dominates resource and environmental impacts. Products dominated by extraction and production benefit from measures throughout the entire life cycles. Products dominated by the use phase benefit mostly from use phase efficiency. For these products, there is a well-known tradeoff between use extension and use phase efficiency of newer products. In other words, if newer products are significantly more efficient in the use phase, for instance in terms of energy use, it may be favorable to replace functioning products.

The feasibility of identifying such general product characteristics decisive for effects of RE measures suggests that it could be limiting to focus on which sector products belong to in efforts to achieve resource-efficiency, as e.g. done by the Royal Swedish Academy of Engineering Sciences (IVA, 2015). In addition, analysis of product characteristics provides a more in-depth basis for decision-making with regard to implementation of RE measures than recommendations provided by R-frameworks.

Paper II

Motivated by the research gaps identified in the work related to Paper I, Paper II studied real-world configurations of RE measures with increased focus on characteristics related to product complexity, e.g. material diversity, number of components, pace of technological development and product chain efficiencies. To do so, it compared the metal use of configurations of RE measures based on use extension before recycling, referred to as use extension (EXT) alternatives, with shorter use of products followed directly by recycling, referred to as business as usual (BAU) alternatives. The EXT alternatives were laptop reuse, smartphone repair and increasing the technical lifetime of LED lighting.

<u>Laptop reuse</u>

The EXT alternative in the reuse case is based on the activities of a reuse and refurbishment company which sources and resells high-quality laptops. The majority of laptops can be resold after only testing and erasing of data, i.e. without requiring any spare parts, and thus, additional metal use. In this case, there is no point of break even between the EXT and BAU alternatives, unless metal contents are significantly lower in new laptops. Use extension reduces the uses of all metals. The uses of functionally recycled metals, i.e. gold, silver, cobalt and palladium, are further reduced because of the increased recycling, enabled by the company’s collection of laptops which are deemed non-reusable upon testing, and hence, sent to recycling. If the content of metals is significantly lower in newer laptops, e.g. due to miniaturization or component design shifts, the BAU alternative may have lower metal use compared to the EXT alternative. Because a share of collected laptops cannot be reused, the EXT alternative requires more laptops in the first use phase to fulfil the same functional unit as the BAU. Thus, if a metal for which functional recycling is lacking is completely removed from newer laptops, e.g. dysprosium as a result of shifting to solid-state drives from hard-disk drives, the BAU alternative may have lower use of that metal compared to the EXT alternative.

Smartphone repair

The EXT alternative in the smartphone case is based on the activities of a repair company which partners with insurance companies to acquire damaged goods such as smartphones. Important parameters for the effects on metal use in this case are: the repair efficiency, i.e. how many of the acquired smartphones are repaired and sent back for further use to insurance holders (36%); component replacement rates, i.e. how often specific components are replaced in repaired smartphones (screens 99%, magnets in speakers and vibrators 30%, battery 20%); duration of use extension (2/3 of a new smartphone lifetime); collection rates into recycling (100% of non-repaired smartphones are collected from the repair company and 16% from smartphone users) and whether functional recycling is available. The influence of the parameters of duration of use extension and collection rates are tested in a sensitivity analysis.

For most metals, the EXT alternative reduces metal use. The exceptions are indium and yttrium in smartphone screens. The EXT alternative increases the use of these metals because of the high replacement rate (essentially all repairs), the shorter use of repaired smartphones compared to new ones and the lack of functional recycling. The uses of other metals for which functional recycling is lacking are slightly reduced due to the use extension e.g. dysprosium, neodymium and praseodymium in magnets (11%), which are replaced occasionally, and tantalum in motherboards (19%), which are never replaced. The uses of metals for which functional recycling is available are reduced to a larger extent: cobalt (56%) in batteries, which are replaced occasionally, and, gold and silver in motherboards, which are never replaced (59%). The uses of these metals are reduced both due to the use extension of repaired smartphones and the increased functional recycling enabled by the collection of non-repairable smartphones. In this case, when only about a third of collected smartphones are repaired, the differences in total collection rates between the alternatives have a large influence on the results. The sensitivity analysis showed that if collection rates were the same from the repair company as from users, use of cobalt as well as silver and gold would instead be reduced by 15% and 20% respectively, i.e. comparable to the results for metals for which functional recycling is lacking.

The sensitivity analysis regarding duration of use extension showed that in order for the use of metals in screens not to increase, the use extension would have to be almost as long as the lifetimes of new smartphones. Likewise, for metals in components which are only replaced in about a third of repairs, e.g. dysprosium, neodymium and praseodymium in magnets, the duration of use extension would have to be about a third of lifetimes of new smartphones to reach break-even.

In summary, the results imply that repair may not be favourable if use extensions are short and replacement rates are high, especially if there is no functional recycling in place for the metals in question. On the other hand, if efficient collection for functional recycling is in place, repair can be motivated even if use extensions are short.

Increasing technical lifetime of LED lighting

The LED lighting case is based on the concept of selling light as a function to e.g. office tenants through a product-service system (PSS) as opposed to selling lighting products. Because service providers maintain ownership over products, they are incentivized to design products for long life, ease of maintenance and recyclability. This involves LED lighting products which: deploy more LED lights driven by a lower current through each to reduce thermal stress; are turned off when not needed by means of an automation control system (ACS); are modular to enable replacement of LED drivers (which otherwise tend to limit the technical lifetimes of LED lighting products) while keeping other components in use; are collected for recycling.

These RE measures are indicated to reduce metal use. The results for different metals however differ substantially (reductions range between 4 and 37%). What influences the results are the relative differences between the alternatives in terms of metal use per component or product, differences in component lifetimes and whether functional recycling is available or not. Despite the deployment of more LED lights per LED lighting product, the increased technical lifetime it enables, reduces the metal use per hour of office lighting. Specifically, this reduces the use of gold, gallium, indium, cerium and yttrium used in LED lights. Use of gold is also reduced due to the differences in collection rates and the ACS which extends the technical lifetimes of LED drivers. The reduced use of silver and palladium are mainly due to the differences in collection rates but also slightly due to the ACS. The long technical lifetimes of the LED lighting products of the EXT alternative (18 years) however imply that they risk not being used for their full technical lifetimes, especially considering the rapid pace of development of LED lighting products in terms of e.g. energy efficiency. In this case, LED lights in the EXT alternative would need to be used for 11 years for the long-life design to be motivated in terms of metals use.

In summary, the three case studies all showed that there is potential for reduced metal use by applying RE measures based on use extension to metal-diverse products. Reducing metal use is accomplished both through use extension and increasing collection rates of products into functional recycling compared to BAU alternatives (naturally, increasing collection rates only affects the uses of metals for which functional recycling is available). However, there are also cases where use extension risks increasing metal use. This may be the case when use extensions are short or require significant metal input, or if newer or less durable products contain significantly lower contents of some metals.

This implies that R-frameworks are too simplistic to provide guidance in efforts to reduce metal use, and thereby towards potential reduction of mineral resource scarcity impacts. Instead, product characteristics such as product complexity in physical (e.g. diversity of metals, components), product chain (e.g. reuse and repair efficiencies, component replacement, collection and recycling rates) and temporal dimensions (e.g. product lifetimes, pace of development of newer products) need to be accounted for. Otherwise, there are risks that particular metal uses may instead increase as results of RE measures. It was even suggested that product complexity can be defined in terms of three dimensions with strong resemblance to these product system characteristics.

Paper III

In Paper III, the effects of using second-hand laptops as opposed to new ones in terms of environmental and mineral resource scarcity impacts were studied. It builds on the insights from Paper II regarding effects of real-world configurations of RE measures such as product chain efficiencies. Further, it demonstrates how effects of RE measures depend on which life cycle phase dominates the total impacts. Laptops have resource and energy intensive component production. This influences the effects of a commercial reuse operation in the following ways:

- It implies that efforts made in preparation for reuse, such as transportation on a large international geographical scale, are negligible in comparison to the benefits of use extension in terms of all environmental impact categories.
- Because preparation for reuse is negligible, the effects on environmental impacts, including mineral resource scarcity, depend mainly on two key features, namely:
    - use extension, i.e. the share of collected laptops which can be reused and the duration of use extension
    - increased functional recycling (enabled by the company's collection of laptops for reuse which are deemed non-reusable upon testing and subsequently sent to recycling).

The impact reduction from increasing collection rates into recycling depends on the relative contribution of primary production of functionally recycled metals to total life cycle impacts. Impacts such as mineral resource scarcity and toxicity, which are dominated by primary metal production, are thus reduced to a greater extent than e.g. climate change for which the dominant contributions come from component manufacturing.

Uses of metals for which functional recycling is available are reduced by both use extension and recycling. Other metals are only reduced by use extension, after which they are lost from functional use by e.g. ending up in landfills or as impurities in other recycling streams. Functionally recycled metals, e.g. copper and gold, account for large shares of mineral resource scarcity impacts of laptops. Thereby, if laptops are collected, recycling is able to reduce considerable shares of their mineral resource scarcity impacts. However, there are also considerable impacts from metals for which there is no functional recycling. This suggests that although use extension may be important for such metals, significant reduction of mineral resource scarcity cannot only rely on use extension. Recycling needs to also be adapted to the material diversity of products.

Summary RQ1

Naturally, the effects from a life cycle perspective on mineral resource scarcity of RE measures applied to metal-diverse products are inherently context-dependent. In general, however, RE measures have the potential to reduce mineral resource scarcity if the product characteristics and real-world configurations (henceforth collectively referred to as product system characteristics) accounted for below are carefully considered.

- physical product characteristics
    - material diversity
    - number of components: the more components the higher likelihood of one limiting the lifetime of the entire product unless it is modular
- product chain efficiencies:
    - reuse and repair efficiency rates, component replacement rates
    - collection rates, which, if improved, could considerably reduce mineral resource scarcity
    - availability of functional recycling
- change over time:
    - pace of development affecting user preferences and consequently service lifetimes
    - design changes e.g. miniaturization or component shifts

These product system characteristics can easily shift the rankings between measures. Hence, they provide better support for decision-making than R-frameworks. Depending on these product system characteristics, RE measures may result in very different effects for different metals. This implies that some metals may have to be prioritized over others in decision-making regarding RE measures of metal-diverse products. Thereby, there is a great need to clarify the principles of prioritization of resource assessment methods which can be used to assess effects of RE measures on mineral resource scarcity.

4.2 Assessment of mineral resource scarcity

4.2.1 Similarities and differences between assessment of depletion and supply disruption impacts

This section accounts for the contributions to RQ 2.1: what are the similarities and differences between principles of prioritization assessing potential depletion and supply disruption impacts?

Paper V compared how mineral resource scarcity is assessed by LCIA-methods, CA methods and hybrid methods (of LCA and CA). This was motivated by the suggested potential for using such methodologies in a complementary manner in a comprehensive assessment of the AoP-NR. Also, it was motivated by ambiguities with regard to both terminology and methodology observed in these literatures. This suggested that the methodologies and the concepts which they address are poorly understood. The methodologies were compared in terms of their cause-effect chain, safeguard subject and temporal scopes. Further, they were compared both in terms of their intended and actual scopes in each respect.

The intended scopes were, not surprisingly, fundamentally different (Table 3). Predominantly, CA and hybrid methods intend to address questions of the kind “how available are mineral resources for products and producers in the near future?” and LCIA-methods “how do products impact how available mineral resources may be in the long term future?”. However, because of misalignment between these intended scopes and the actual scopes (resulting from the modelling concepts and practical implementations) of the methodologies there are sometimes similarities between them. For instance, although the predominant intended temporal scopes are long term in LCIA and short term or medium term in CA methods and hybrids, the actual scopes are predominantly short to medium term or incongruent. Clearly, such unintended similarities are not conducive to neither purposive assessment of the different questions the methodologies intend to address individually, nor to complementary assessment. Plausibly, such unintended similarities could also explain some of the confusion observed in industry (Berger et al., 2020) and academia (Paper V) regarding these methodologies and concepts such as depletion, scarcity and criticality.

Table 3. Simplified overview of the misalignment between predominantly intended and actual scopes, causing unintended similarities between the methodologies (based on Paper V).

	CA and hybrid methods	*LCIA-methods*
Question	"How available are mineral resources for products and producers in the near future?"	"How do products impact how available mineral resources may be in the long term future?
Safeguard subject	Resource availability for system under study	Resource availability for future generations
Problem formulation	Technospheric circumstances, such as: -*concentration of production or reserves* - *depletion time of reserves* - *political stability* - *social welfare* - *global demand* risk to reduce availability	Extraction from ecospheric stocks, such as: - *crustal content* - *crustal concentrations* risk to reduce availability
Actual scope:	A mix of technospheric and ecospheric factors: - *crustal content* - *political stability* - *social welfare* - *global demand*	A mix of technospheric and ecospheric factors: - *depletion time of reserves* - *concentration of production or reserves* - *global demand (extraction rates)* - *crustal content* - *crustal concentrations*

Comparing the three methodologies within a common framework of cause-effect chain steps (Figure 2) clarifies the relations between concepts addressed by the methodologies, e.g. depletion and criticality and fundamental concepts such as scarcity and rarity. In LCA, scarcity is predominantly caused by ecospheric rarity and non-foreseeable demand. In CA and hybrids on the other hand, scarcity is predominantly caused by technospheric rarity and largely foreseeable demand. Further, both depletion LCIA methods and hybrid methods assess *scarcity* while both future efforts LCIA methods and CA methods also assess consequences of scarcity. They do this in order to safeguard resource availability for either future generations (LCIA) or the system under study (CA and hybrids). More precisely:

- Depletion LCIA methods reflect the potential of current product systems to deplete ecospheric stocks, and ultimately cause potential scarcity in the long term future.

- Future efforts LCIA methods include what is reflected by depletion methods, i.e. potential scarcity, and add potential *consequences of scarcity* in terms of substitution to lower grade ores and associated increased costs.
- Hybrid methods reflect the potential of technospheric circumstances to disrupt supply of technospheric flows and thereby cause scarcity in the short term future.
- CA methods include what is reflected by hybrid methods, i.e. potential scarcity, and add potential *consequences of scarcity* in terms of substitution to other resources and associated increased costs.

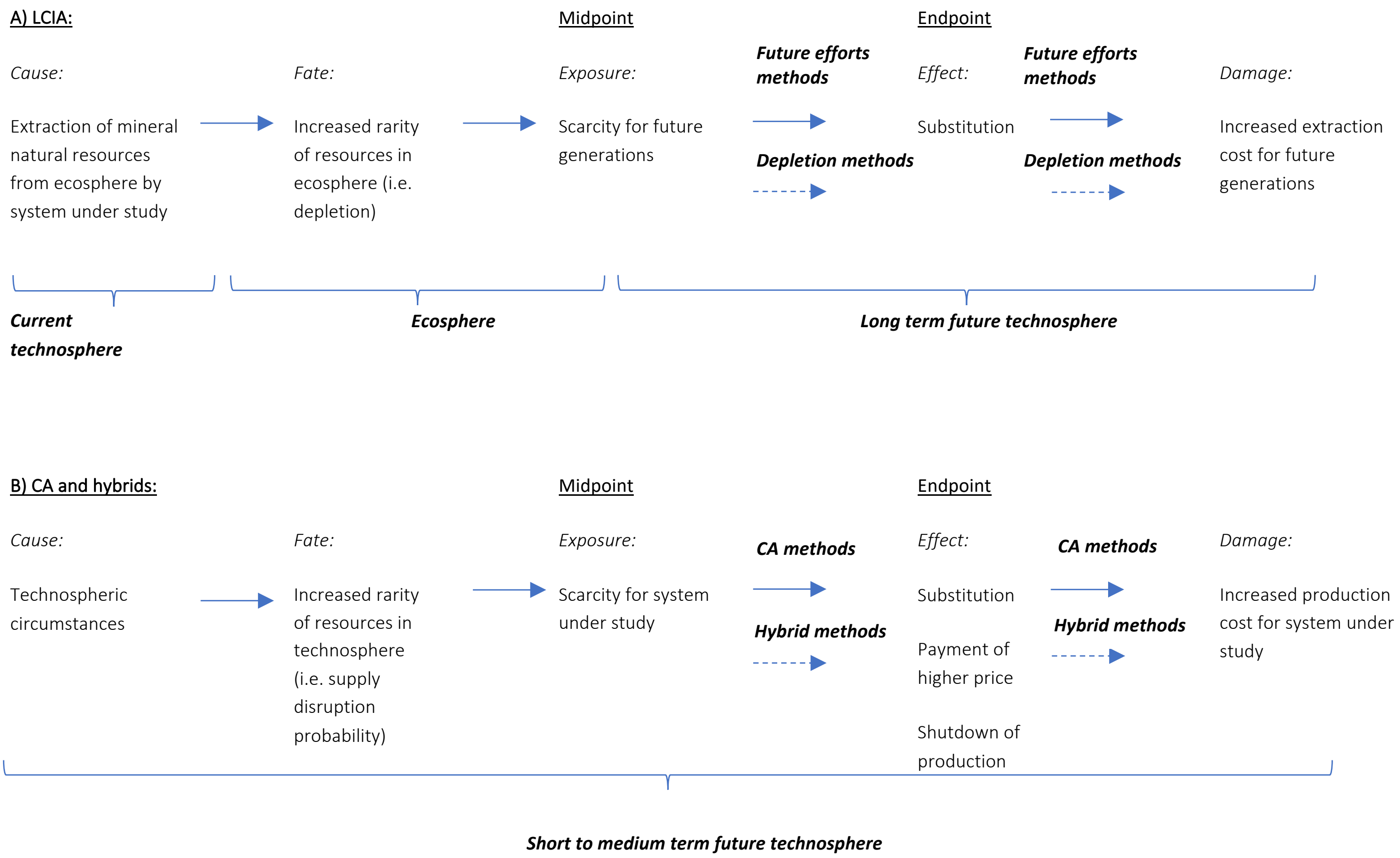

Figure 2. Predominant intended cause-effect chain scopes of A) LCIA and B) CA and hybrids. Full and dashed arrows denote modelled and implicit cause-effect mechanisms respectively (Paper V).

Further, in terms of safeguard subject, the comparison focused on what natural resource category, i.e. flows, funds or stocks, the methodologies safeguard.

- *Stock resources* are considered to exist as a finite amount in the ecosphere and can be considered non-renewable since renewal rates are insignificant with respect to the time scales of human extraction rates (Klinglmair et al., 2014a).
- *Fund resources* can be regenerated and hence, either be depleted or expanded depending on the rates of renewal and extraction (Klinglmair et al., 2014a; Sonderegger et al., 2017).
- *Flow resources* are non-depletable since they are practically instantaneously renewed but may have a limited availability at a certain time and place because of e.g. competition (de Haes et al., 2002; Klinglmair et al., 2014a), uneven geographical distribution or because they cannot be moved (Swart et al., 2015).

Since mineral resources are non-renewable in their ecospheric origin, i.e. the Earth's crust, they have been categorized in LCA as posing a problem related to the depletion or dissipation of a fixed stock (Sonderegger et al., 2017). However, this perspective is argued to be insufficient for a comprehensive assessment of mineral resource scarcity. Since mineral resources can be renewed in the technosphere they can pose stock, fund and flow problems.

Considering what constitutes the concern in CA and hybrids, namely, scarcity at a certain time and place caused by e.g. uneven geographical distribution (concentration of production), competition (global demand) or because they cannot be moved (trade barriers) it is clear that these methodologies are predominantly concerned with the availability of mineral resource flows. In other words, what CA methods and hybrids predominantly safeguard is the availability of mineral resource flows within the technosphere. LCIA, on the other hand, predominantly safeguards the availability of future mineral resource flows by safeguarding resource stocks in the ecosphere.

This realization provides another perspective on the methodological ambiguity, and even inconsistency, of some resource assessment methods. It is possible to observe that several methods mix factors representing flows, funds and stocks in the same indicator. For instance, the Abiotic Depletion Potential (ADP) method (Guinée and Heijungs, 1995; van Oers et al., 2019) derives its CFs by combining factors representing flows (global demand, or more precisely, global extraction rates) with stocks (crustal content). In paper IV, it was argued that the global extraction rates correspond to the elementary flows of an LCA of the global economy. The Anthropogenic Extended Abiotic Depletion Potential (AADP) method (Schneider et al., 2011) adds to the combination of stocks and flows of ADP by incorporating resources within the technosphere, i.e. a fund, in their measure of the total stock available to humans (ultimately recoverable resources (URR)). Thereby, in neither of these methods do the CFs correspond to the extraction from the ecospheric stock on which life cycle inventory is based.

These methodological inconsistencies seem to arise because of a lack of distinction between mineral resource flows, funds and stocks. Furthermore, considering that the temporal relevance of factors representing each resource category are largely different, keeping them separate in distinct methods could help to align intended and actual temporal scopes.

In long term scopes, which most LCIA-methods intend to address, ecospheric stocks are the most relevant factors to focus on. As will be explained further in Chapter 5, ecospheric stock factors do not reflect what will ultimately matter for mineral resource scarcity in the long term future, since this will naturally depend on the state of the future technosphere as well. Nonetheless, since the state of the future technosphere is unforeseeable, ecospheric factors are argued to be the best possible proxies for long term mineral resource scarcity. In addition, if LCIA focuses strictly on ecospheric factors, there is consistency with other impact categories and with the fundamental principles of LCA, namely, that the LCI models the technosphere and LCIA models the impacts on the ecosphere. The lack of an LCIA-method which purposively assesses potential long term scarcity based on rarity of ecospheric stocks motivated the development of the CSI (Paper IV).

In addition to assessing impacts on availability in ecospheric stocks, it makes perfect sense to acknowledge and account for the fact that resources in the technosphere may also be available to humans, as intended with the AADP method by (Schneider et al., 2011). In fact, it is one of the fundamental aims of the circular economy vision to increasingly produce metals from technospheric resources. Hence, in a circular economy, it will be increasingly relevant to assess resource availability in the technosphere in addition to assessing resource availability in the ecosphere. Accordingly, methods could be developed which focus on technospheric resource funds such as end-of-life products and landfills.

In short term perspectives, what primarily determines resource availability are factors representing flows as such, e.g. extraction rates from specific countries, and circumstances which influence their magnitudes e.g. trade barriers and political stability. Thus, it makes sense for e.g. CA and hybrids, which predominantly intend to assess resource availability in the short term to focus on these types of factors. Mineral resource flows demanded within the technosphere are extracted from both ecospheric stocks and technospheric funds. CA and hybrids have so far focused mainly on the availability of mineral resource flows extracted from ecospheric stocks. As pointed out by Berger et al. (2020) expanding CA and hybrids to account for constraints in secondary supply, i.e. flows from technospheric funds, could improve such assessments.

Lastly, distinguishing between mineral resource flows, funds and stocks provides a more accurate terminology conducive to developing and using complementary methods in a comprehensive assessment of mineral resource scarcity. It was argued in Paper V that the persistent debate on mineral resources has been fomented by arguments which muddle two different resource problems:

extraction from ecospheric stocks and dissipation from technospheric funds. By realizing that mineral resources flow, fund and stock problems are merely subsets of the question of total resource availability for humans, it can be argued that both the fixed stock and the opportunity cost perspectives are individually limited and that both perspectives are relevant and complementary (further discussed in Chapter 5.1.2).

4.2.2 Similarities and differences among LCIA-methods

This section accounts for the contributions to RQ 2.2: what are the similarities and differences among LCIA-methods assessing potential depletion impacts?

The principles of prioritization of a selection of LCIA-methods used in Paper III and VI, evaluated in Paper IV and discussed in Paper V are explicated in Table 4 and Figure 3. Table 4 provides an overview of the respective aspects of each method. Figure 3 illustrates the relations between resource metrics deployed in the modelling concepts and practical implementations of methods. This serves to illustrate how the CFs, i.e. prioritizations, of LCIA-methods can be described as more or less technospherically contingent.

Table 4. Overview of principles of prioritization of selected LCIA-methods.

* ADP-B&R could also be interpreted as concerned with the safeguard subject of medium-term availability for product systems (Berger et al., 2020).

Resource assessment method	*Safeguard subject*	*Problem formulation*	*Modelling concept*	*Practical implementation*
Abiotic depletion potential (ADP) (Guinée and Heijungs, 1995; Van Oers et al., 2002)	Mineral resource availability for future generations	Depletion of mineral resources caused by extraction	Relation of current use to estimate of ultimately available mineral resources	- Global extraction rates - Ultimate reserves (UR), reserve base (B) or reserves I*
Crustal scarcity indicator (CSI) (Paper IV)	Mineral resource availability for future generations	Depletion of mineral resources caused by extraction	Relation of current use to estimate of ultimately available mineral resources	- Average crustal concentrations
Cumulative exergy demand (CexD) (Bösch et al., 2006)	Mineral resource availability for future generations	Depletion of exergy caused by extraction	Thermodynamic (exergy is what is depleted whereas energy and material resources are merely transformed)	- Concentrations of currently mined ores - (prices for allocation)
Environmental Priority Strategies (EPS) (Steen, 1999b)	Mineral resource availability for future generations	Depletion of mineral resources caused by extraction	Willingness to pay for sustainably produced resources, i.e. from common rock	- Average crustal concentrations - Extraction using backstop technology
Surplus ore potential (SOP) (Vieira, 2018; Vieira et al., 2017)	Mineral resource availability for future generations	Depletion of mineral resources caused by extraction	Relation of ore mass required to produce metal at present versus in the future	- Cumulative grade-tonnages - Cumulative extraction - Ultimately recoverable resources (URR) or reserves I - (prices for allocation)

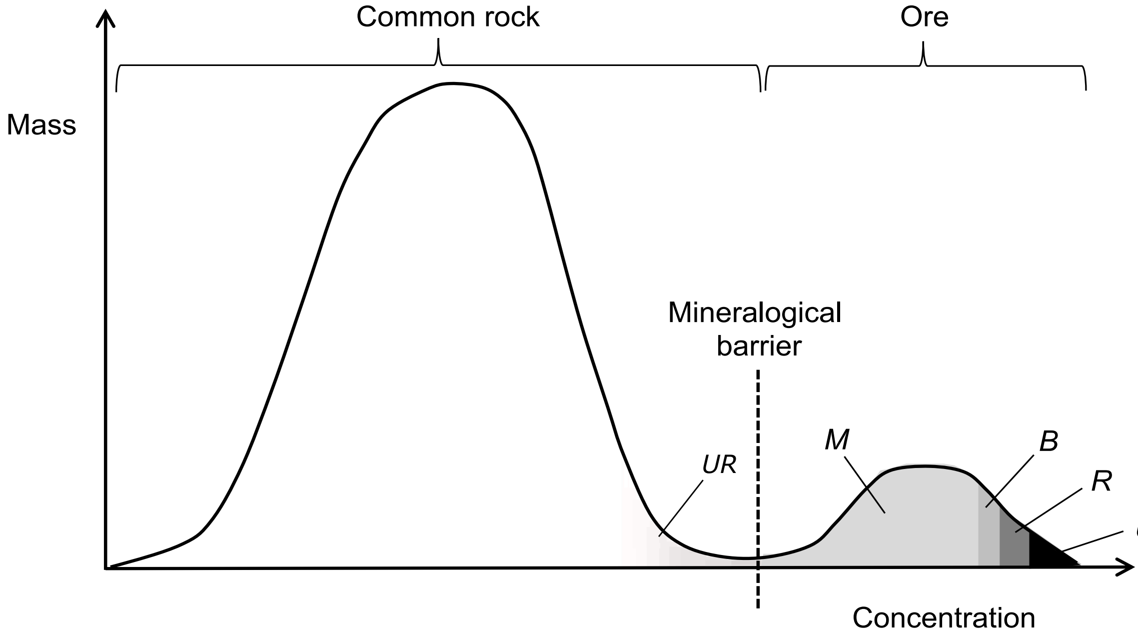

Figure 3. Schematic illustration of the bimodal mass-concentration curve showing the distribution of rare element concentrations in the crust. The large hump represents rare elements in common rock and the smaller hump represents concentrated ores. The mineralogical barrier is the point at which the concentrated ores in the smaller hump have been extracted. UR= ultimate reserves (including M, B, R and U)(van Oers and Guinée, 2016), M = mass of the element under the smaller hump (including B, R and U), B = reserve base (including R), R = reserves and U = cumulative extraction. Note that the magnitudes of e.g. B and R are not dictated by concentration alone – deposit size, depth, overburden, mineralogy, etc. are all factors in their estimation. Adapted from Paper IV, adapted from (Gordon et al., 2007; Henckens et al., 2016; Skinner, 1976).

In the ADP, a resource metric assumed to represent what may be ultimately extractable must be made: reserves, reserve base or ultimate reserves based on crustal content (van Oers et al., 2019). The EPS assumes a backstop technology for extraction from common rock (Steen, 1999b; Steen and Borg, 2002). The SOP extrapolates from grade-tonnage relationships of cumulative extraction to estimate how grade-tonnage relationships will change as a function of future cumulative extraction towards what might be ultimately extractable (using either ultimately recoverable resources[1] or reserves) and sums up the surplus ore required from now until ultimate exhaustion (Vieira et al.,

[1] The difference between ultimately recoverable resources and ultimate reserves as measures of what may be ultimately extractable for humans is that the latter assumes that a larger portion of the crustal content is available. Van Oers et al. (2016) claims that what is ultimately extractable lies somewhere between R and UR. UR however includes not only elements in ores but also common rock (Schneider et al, 2015). URR is an attempt to be more precise about what parts of the UR which might actually be extractable. Presumably, URR is assumed equal to M, considering Schneider et al., (2015)'s reference to the mineralogical barrier.

2017). Because of the extrapolation from cumulative extraction, CFs of the SOP are somewhat contingent upon the past and current technosphere, which has dictated what ores have been cumulatively extracted.

The CSI (Paper IV) is based on correlations between average crustal concentrations and reserves, reserve base and estimated amounts of elements in concentrated ores. It does not use extrapolation from any point in time, in contrast to e.g. SOP which extrapolates from cumulative extraction. Neither does it require assumptions about the long term future technosphere, as EPS, through its assumption and modelling of a backstop technology. And, unlike ADP and SOP, the CSI does not include assumptions regarding which resource metric that in the future will turn out to be closest to what may be ultimately extractable. Instead, regardless of which resource metric that in the future turns out to be closest to what will be ultimately extractable, average crustal concentrations and thus CFs of the CSI, can be assumed to be roughly proportional to it.

In summary, while the other LCIA-methods include technospherically contingent factors such as extraction rates, assumed extraction technologies, historically and currently mined ores and resource prices, the CSI is based solely on an ecospheric factor. Thereby, it does not include any temporally variable factors. In addition, it has high practical applicability and methodological coherence since all 76 CFs (most other methods have fewer CFs) are calculated in the same way. For these reasons, the CSI is argued to have advantages compared to other methods in terms of reflecting potential long term mineral resource scarcity.

Summary RQ2

Comparing LCIA, CA and hybrids using a common framework of cause-effect chain steps (Figure 2) clarifies the relations between concepts addressed by the methodologies e.g. depletion and criticality and fundamental concepts such as scarcity and rarity.

The intended scopes of LCIA, CA and hybrids are largely different. However, there are similarities in actual scopes arising from methodological inconsistencies. This hinders both purposive assessment of individual questions intended to be addressed and complementary use of the methodologies. Distinguishing between mineral resource flows, funds and stocks is suggested to create better alignment between intended and actual temporal scopes, resolve methodological inconsistency and provide a more accurate terminology.

Similarities and differences among LCIA-methods are best summarized in Table 4 and Figure 3. In brief, LCIA-methods have largely similar safeguard subjects and problem formulations. They differ considerably in terms of modelling concepts and practical implementation, and as a result, can be characterized in terms of different degrees of technospheric and ecospheric orientation.

4.3 Influence of assessment methodology on effects of RE measures

Paper II

In Paper II the effects of laptop reuse, smartphone repair and long-life design of LED lighting on metal resource use was assessed through MFA. As explained in Chapter 2, MFA can be interpreted as having the principle of prioritization that metals are not mutually substitutable, making the potential scarcity of each metal a unique concern. Paper II demonstrated that the effects of the RE measures varied greatly between metals. Most often, the variation concerned the extent of reduction of metal use. But there were also cases where the uses of some metals were reduced at the cost of increased use of other metals. For instance, the smartphone repair case indicated that indium and yttrium use may increase to allow for other the use of other metals to decrease. With this principle of prioritization, it is not possible to conclude whether repairing smartphones is resource-efficient in terms of reducing mineral resource scarcity. It is merely possible to say that it may be resource-efficient to repair smartphones in terms of some metals but resource-inefficient for others.

Paper III

In Paper III, several LCIA-methods were used to compare the effects of a use extension (EXT) alternative where second-hand laptops are used, enabled by a commercial laptop reuse operation, with a business as usual (BAU) alternative where new laptops are used: Abiotic Depletion Potential (ADP) based on ultimate reserves (UR) (average crustal concentrations multiplied by mass of the Earth's crust), reserve base (B) and economic reserves I (Guinée and Heijungs, 1995; Van Oers et al., 2002), Eco-Scarcity method (EcoSc), Cumulative Exergy Demand (CexD) (Bösch et al., 2006), Environmental Priority Strategies (EPS) (Steen, 1999a, b) and ReCiPe (Goedkoop M., 2009).

The methods influence which metals have high mineral resource scarcity impacts (Figure 4). Consequently, this influences which metals that are most favourable to focus on in order to reduce mineral resource scarcity through RE measures. Some metals have high impacts only according to one method. Other metals, gold in particular, have considerable impacts regardless of method.

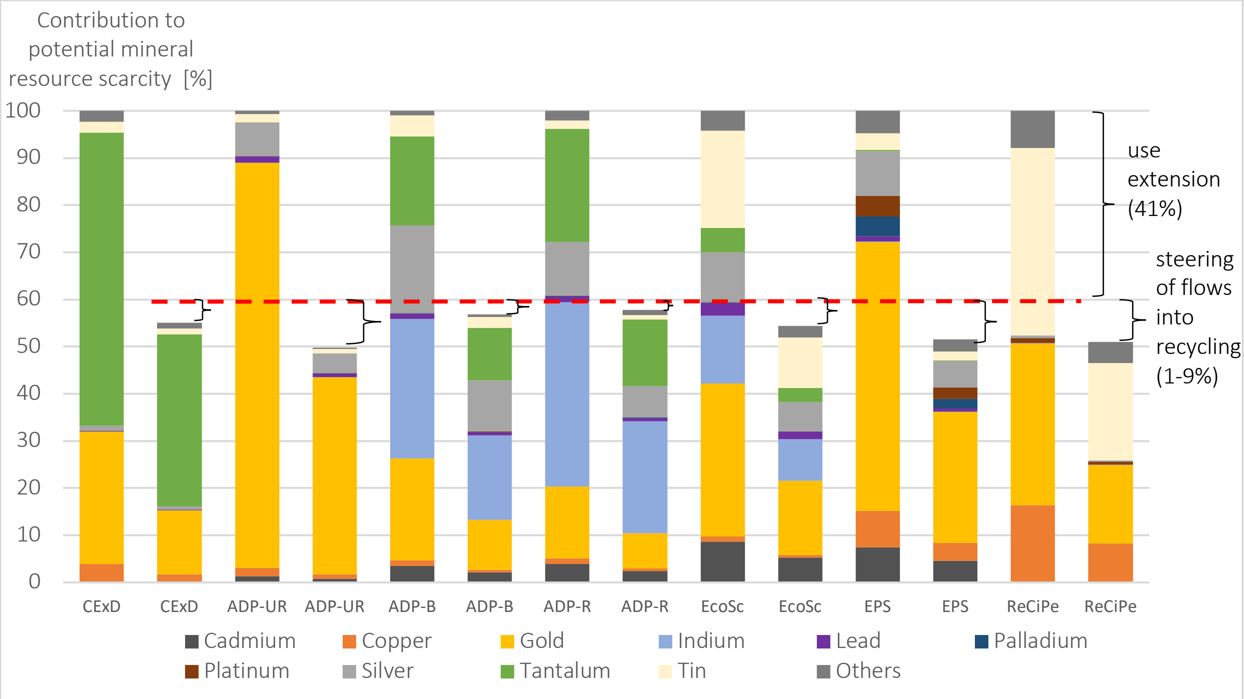

Figure 4. Potential mineral resource scarcity impacts per functional unit: the EXT alternative (right) compared to the BAU alternative (left) [%] with five resource assessment methods of which one has three versions. Metals with >1.5% contribution with at least two methods or >4% with at least one method are displayed individually. Others include 20 metals such as iron, magnesium, nickel and rare earth elements. Adapted from Paper III.

Gold is one of the rarest metals in terms of average crustal concentration but occurs in deposits in significantly higher concentrations (Ayres and Peiró, 2013). This implies that impacts of gold are more emphasized in methods with a relatively longer term scope, such as those based on average crustal concentrations (ADP-UR and EPS) than methods with shorter term scopes such as those based on economically contingent factors such as reserves or currently extracted ore grades, such as CexD, EcoSc and ADP-B and ADP-R. These methods, on the other hand, rather emphasize potential scarcity of indium and tantalum. The reserves of by-products metals (metals produced due to being in the same ore as another metal which provides the economic incentives for production) tend to be small because they are seldom explored for (Drielsma et al., 2015). Thus, methods using reserves as estimates of availability may overestimate the potential scarcity of by-product metals (Drielsma et al., 2015). In addition, the results from these methods demonstrated a sensitivity to the temporal variability of factors such as extraction rates, since extraction rates of different years yielded considerable result variations (e.g. tantalum between ADP-R&B and EcoSc).

According to these methods, potential mineral resource scarcity impacts from laptop use are caused by gold in particular, but also other metals such as indium, tantalum, tin and copper. As demonstrated in Figure 4, the use extension feature of the commercial reuse operation reduces potential scarcity impacts of all metals to the same extent. The second feature, namely the increased collection of laptops into functional recycling reduces impacts of functionally recycled metals further. This implies that methods which emphasize gold in particular, but also copper, tin, palladium and platinum, result in greater impact reduction than other methods. These metals are most emphasized by methods based on average crustal concentrations, namely ADP-UR and EPS. In addition, with these methods in particular, quite a large share of mineral resource scarcity impacts (38-44% in the commercial reuse alternative) from the production of laptops are offset in recycling (Figure 3b in Paper III).

It was concluded that the use of several LCIA-methods can potentially provide complementary perspectives on mineral resource scarcity due to addressing different problems with different modelling concepts and practical implementations. Naturally, this affects which metals are emphasized. The choice of LCIA-method both affects the distribution of impact reduction over metals and the degree of impact reduction. In the case of laptops, methods which emphasize metals for which functional recycling is available, typically those based on average crustal concentrations, result in the largest impact reduction. At the time of writing Paper III, we had not examined the methods to the extent that we subsequently did in Paper IV and V. Thus, we could not specify in more detail at that time in what ways LCIA methods can actually provide complementary perspectives on mineral resource scarcity.

Paper VI

In Paper VI, the aim was to examine the usefulness of potentially complementary methods for a comprehensive assessment of mineral resource scarcity in industry. It studied both potential supply disruption and resource depletion impacts related to a car company's permanent magnet synchronous machine (PMSM) for electric vehicles, i.e. an electric motor. To assess probability of supply disruption, a hybrid method was used, namely, the ESSENZ method (Bach et al., 2016). To assess supply disruption probability and consequences of supply disruption, i.e. criticality, a CA method was used, namely, the Yale method (Graedel et al., 2012). Analogously, to assess potential resource depletion, the Crustal Scarcity Indicator (CSI) (Paper V) was used. To assess potential resource depletion and consequences thereof, i.e. future efforts, the Surplus Ore Potential (SOP_{URR}) (Vieira, 2018) was used. The aim of using these different methods was to identify hotspots which could be relevant for the company to address in terms of both depletion and supply disruption impacts, e.g. by applying RE measures. The use of these specific methods were based on them being most in line with the recommendations suggested in Paper V (focusing on ecospheric stock factors in LCIA and technospheric flow factors in CA and hybrids) for each method type: depletion (LCIA-method), future efforts (LCIA-method), supply disruption probability (hybrid method) and criticality (CA method). In addition, the CA method needed to be suitable for application in a company context.

As expected, the metals with largest potential mineral resource scarcity impacts differ considerably depending on the safeguard subject. The safeguard subject of the LCIA methods is resource availability for future generations. Conversely, the safeguard subjects of the CA and hybrid methods are the PMSM and the company (i.e. the system under study). The metals which are emphasized in terms of depletion impacts are cerium, copper, dysprosium, molybdenum, neodymium, lead and rhodium (Figure 5). The metals which are emphasized in terms of supply disruption impacts are dysprosium, iron, neodymium and silicon (Figure 6).

In terms of depletion, copper accounts for 25-29% of impacts of the PMSM, with SOP and CSI respectively. The emphasis on copper in terms of depletion impacts reflects that copper is quite rare in the ecosphere. Rare Earth Elements (REEs) on the other hand, are not as rare in the ecosphere as their name suggests (some have higher average crustal concentrations than e.g. copper). Some differences in relation to their impacts can be explained by their respective geological characteristics. Copper is quite rare in terms of average crustal concentrations but does occur in concentrated deposits while REEs are not so rare in terms of average crustal concentrations but seldom occur in concentrated deposits (Peiró et al., 2013). Rather than being rare in the ecosphere, REEs are rare in the technosphere, as visible in the supply disruption impacts.

In terms of supply disruption probability, the ESSENZ method mainly emphasises neodymium while the Yale method emphasises neodymium and dysprosium. In contrast to ESSENZ, which assesses supply disruption probability, the Yale method also assesses the vulnerability dimension of criticality by including the substitutability of metals. By doing so, the Yale method also emphasises iron and silicon. The reason is that there are no substitutes for iron in the core laminations of the PMSM and that substitutes for silicon are more expensive and have higher environmental impacts. The non-substitutability of iron in core laminations demonstrates that substitubability is very context-specific. This is evident by comparing application-specific substitutability scores (Graedel et al., 2015), used in the GeoPolRisk method (Cimprich et al., 2017), which is another hybrid method, with the substitutability evaluation by the case company's product designers. In the application-specific substitutability scores, the substitutability of iron in transportation applications is characterized as "good" (Graedel et al., 2015) while the case company's product designers characterize iron in core laminations of electric motors as "non-substitutable". Neodymium and dysprosium, on the other hand, are quite substitutable by means of other magnet or motor types. Iron and silicon are however not particularly rare in the technosphere (except that the ESSENZ method indicated that iron could potentially be constrained by trade barriers) nor the ecosphere (in fact, both are among the most abundant metals in the ecosphere). In summary, this implies that the least substitutable metals are not particularly likely, relative to other metals, to become scarce in neither the short nor long term.

Hence, there is little reason from mineral resource scarcity perspectives to direct RE measures towards iron and silicon. In terms of depletion, RE measures could be directed towards the use of copper. This would not only reduce the contributions of the PMSM's copper use but also metals which are co-produced with copper, namely, molybdenum, lead and rhodium which account for considerable shares of depletion impacts as well. Likewise, if RE measures would be directed towards the use of neodymium and dysprosium, this would not only reduce impacts of those specific REEs but of other REEs as well, due to co-production. RE measures targeting neodymium and dysprosium could be motivated to reduce both potential supply disruption and depletion impacts. However, with the Yale method mere reduction of metal use would not reduce criticality, only complete substitutions would. Hence minimizing the use of e.g. dysprosium with alternative manufacturing techniques could significantly reduce its depletion impacts but would not reduce criticality.

The study also gave insights about the potential usefulness of complementary methods in a company context. In addition to revealing insights about vulnerability which hybrids could not (e.g. the non-substitutability of iron) performing a CA was reported to be a valuable learning experience for the company, in particular, with regard to the complexity of substitutability. It became clear that even direct substitutions, e.g. from copper to aluminium in magnet windings, would likely result in system-level effects on performance or battery requirements. It was also noted that performing CA alongside LCA could have potential synergies. Since LCA results are often meant to inform design changes such as substitution, discussions on substitutability undertaken as part of CA could be valuable in terms of analysis of LCA results and potential RE measures to reduce depletion impacts.

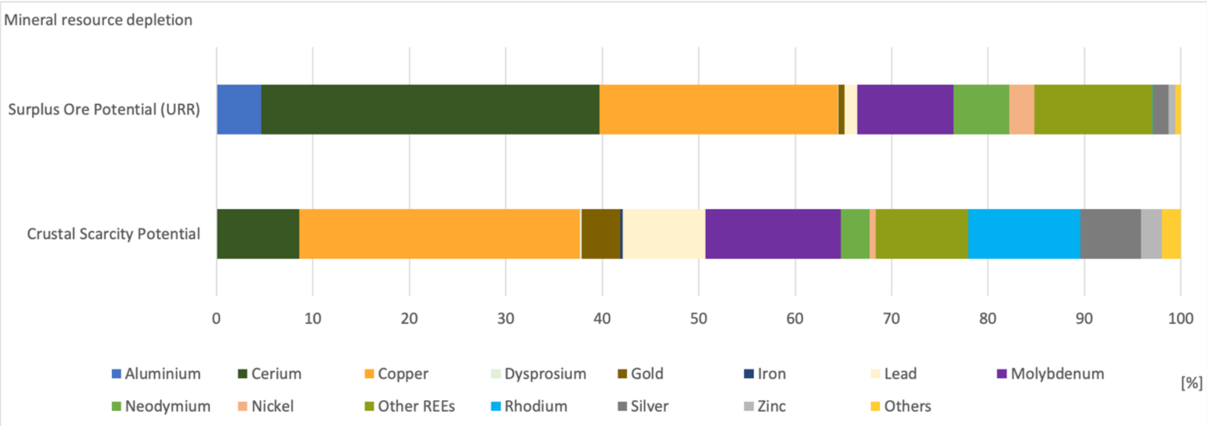

Figure 5. Relative potential depletion impacts of the PMSM, using SOP and CSI.

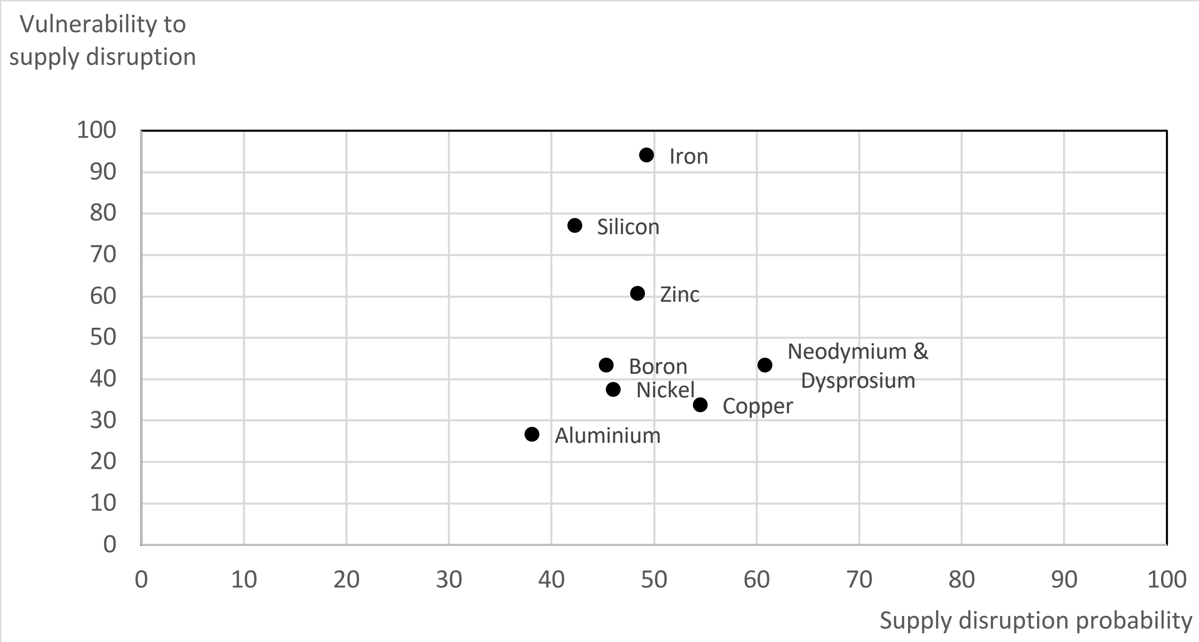

Figure 6. Criticality assessment of metals in PMSM for VCC based on the Yale method. The vulnerability axis composes substitutability: in turn, composing substitute performance, substitute availability, price ratio and environmental impact ratio.

Summary RQ3

MFA: RE measures which decrease the use of some metals at the cost of increasing the use of others cannot be concluded favourable or not because each metal poses a unique problem.

LCIA: the effects on mineral resource scarcity impacts vary between LCIA methods, mostly in terms of which metals have highest impacts (and thus are most favourable to reduce the use of) but also in terms of degree of potential impact reduction.

CA and hybrids:

- CA allows for consideration of vulnerability whereas hybrid methods generally do not.
- CA and hybrids do not credit RE measures (except for complete substitutions) with reducing supply disruption impacts (except for ESSENZ).

CHAPTER 5 - Discussion

5.1 Thesis contributions in relation to literature

5.1.1 Effects of RE measures on mineral resource scarcity

One of the main contributions of this thesis lies in questioning the relevance of R-frameworks and sectors as guidance in implementations of RE measures. While R-frameworks can indeed provide some general guidance it needs to be stressed that they are limited as a basis for decision-making in specific contexts. Paper I and II explicate how product characteristics can change the rankings between RE measures and, thus, how consideration of product characteristics and real-world configurations (i.e. product system characteristics) such as product chain efficiencies provide a more in-depth basis for decision-making. Thus, arguing for explicit priorities between RE measures as e.g. Kirchherr et al. (2017) may be uncalled for. Further, the feasibility of analyzing RE for such a wide variety of products implies that focusing on sector as guidance for implementation of RE measures could be limiting. Instead, Paper I demonstrated that there are similarities between vastly different products in terms of which RE measures are successful. Hence, product system characteristics can be argued a better guidance for implementation of RE measures than both R-frameworks and sector.

Further, as argued by Blomsma and Brennan (2017), CE in reality is not about single RE measures but rather configurations of RE measures, perfomed in sequence or in parallel. Accordingly, Blomsma and Brennan (2017) hypothesised that the study of configurations of RE measures by means of e.g. LCA and MFA, could be conducive to developing the theoretical basis of CE by e.g. revealing synergies between RE measures. Paper II and III confirmed this hypothesis by explicating how impacts of real-world configurations of RE measures tend to be dictated by the two principal features of use extension and increased functional recycling. Thus, implementing RE measures is not so much a question of "either or", which could be the interpretation of R-frameworks, as of "and". These findings were outcomes of studying real-world configurations of RE measures.

5.1.2 Assessment of mineral resource scarcity

There is plenty of recent and important research on assessment of mineral resource scarcity to which the findings of this thesis ought to be compared.

Similar to Paper V which examined the alignment between actual and intended scopes of LCIA, CA and hybrids, Schulze et al. (2020a, 2020b) and Drielsma et al. (2015) have examined the alignment between actual and intended scopes of LCIA methods, Berger et al. (2020); Sonderegger et al. (2020) LCIA-methods and hybrids and Schrijvers et al. (2020) CA methods and hybrids.

Aiming to provide guidance on use of resource assessment methods, the LCI-UNEP (Berger et al., 2020) outline seven questions (question here has similar meaning to the term *problem* from (Schulze et al., 2020a)'s framework used in this thesis) which stakeholders may have with regard to mineral resource scarcity. They recommend which method(s) to use for each question, but it is up to practitioners to decide on the most relevant question to address with consideration of the goal and scope.

Paper V discusses three of the seven questions outlined by Berger et al. (2020). The thermodynamics question was excluded due to the low support for thermodynamic methods in previous reviews, motivated by that they do not reflect the scarcity of mineral resources as such, but instead the scarcity of exergy (JRC, 2011; Klinglmair et al., 2014b; Sonderegger et al., 2017; Steen, 2006). Changing resource quality, economic externality and outside-in medium-term availability questions were excluded because they were not discussed in the other reviews which were synthesized in Paper V (except by the LCI-UNEP). This can be seen as a limitation of the method used in Paper V. Nevertheless, it also enabled a clear focus on the questions which are discussed the most in the literature and which seem to have methods of highest maturity level according to the levels of recommendations given by Berger et al. (2020).

Importantly, the method of synthesizing review studies allowed for the "breadth" (Flyvbjerg, 2006) (as discussed in Chapter 3) of analysing LCIA, CA and hybrids collectively in a common framework. This breadth was crucial to arriving at the most important findings. For instance, it allowed for clarifying the relations between concepts such as depletion, criticality, scarcity and rarity in terms of the predominant cause-effect chains of the methodologies. As pointed out previously, these terms are often confused by method developers and practitioners. Hence, showing their relation to one another can serve to straighten out misunderstandings and provide a common ground for future methodological development. For instance, analysing CA and hybrids in terms of cause-effect chains was suggested by Schrijvers et al. (2020) as a way to align intended and actual scopes of individual CA and hybrid methods. Although this was not the purpose of analysing CA and hybrid methods in terms of cause-effect chains in Paper V, the suggested cause-effect chains therein could perhaps be used as inspiration and expanded upon by those with that purpose.

There are some similarities between findings from Paper V and that of the Sustainable Management of Primary Raw Materials (SUPRIM) project (Schulze et al., 2020a, b). They also find inconsistency with regard to e.g. the AADP method (but not the ADP however), emphasize the importance of alignment between modelling concepts and practical implementation with the problem formulation, disapprove of incorporating technospheric factors such as socio-political risk and policy in LCIA-methods and consider it likely that methodological inconsistencies contribute to confusion with regard to assessment of mineral resource scarcity in LCA.

In contrast to Paper V, neither Schulze et al. (2020a, 2020b) nor Berger et al. (2020); Sonderegger et al. (2020) consider the potential usefulness of distinguishing between stocks, funds and flows of mineral resources suggested in Paper V. This suggestion was an outcome of comparing LCIA, CA and hybrids collectively, which neither of the other reviews did. Because of this, there are differences between the recommendations. For instance, Sonderegger et al. (2020) discuss benefits and drawbacks of including extraction rates in LCIA-methods. Despite the drawbacks, the highest level of recommendation of all 27 methods reviewed by Berger et al. (2020); Sonderegger et al. (2020) is given to the ADP-UR (Berger et al., 2020). This clearly differs from the recommendations of Paper V and also Paper IV.

Paper V draws considerably on the analysis by Drielsma et al. (2015) on misalignment between actual and intended scopes of LCIA-methods. They discuss how LCIA-methods have moved away from the fixed stock perspective to rather assess mineral resource scarcity from the opportunity cost perspective. Although these perspectives have previously been regarded as incommensurable (Neumayer, 2000; Tilton, 1996) Drielsma et al. (2015) implied that they could complement each other. They identified e.g. Ecological Scarcity Potential method (Schneider et al., 2014) (categorized as a hybrid method in Paper V) as a representation of the opportunity cost perspective and the fixed stock perspective to be the only perspective compatible with LCA. At the same time, Drielsma et al. (2015) discredited the fixed stock perspective for lacking relevance to decision-makers. In other words, hybrids and LCIA-methods could complement each other but, in their view, the fixed stock perspective is so limited that mineral resource scarcity is best addressed by methods based on the opportunity cost perspective, outside of LCA. Here I will attempt to explicate how both perspectives can be useful in a comprehensive assessment of mineral resources in which it is acknowledged that mineral resources can pose stock, fund and flow problems (Paper V).

As introduced in Chapter 2*,* the opportunity cost perspective is the notion that the ultimate limit to resource availability is what society is willing to offer in order to access resources. The fixed stock perspective is based on the notion that extraction and use of finite resources leads to reduced availability in the ecosphere. This is often interpreted as meaning that humanity as a consequence of extraction will "run out" of resources altogether. To illustrate how this is a misinterpretation and how both perspectives may complement each other I propose that resource availability can be described as dependent on two prerequisites: ecospheric availability (e.g. geological occurrence in the Earth's crust or concentration of ores) and technospheric circumstances (e.g. depending on state of economy, investment possibilities in exploration, technology etc).[2]

[2] Surely, it can be questioned whether *ecospheric* availability is a prerequisite since *any* availability, technospheric or ecospheric, should in principal suffice. However, since the ecosphere is the compartment where most extraction occurs and because extraction from the ecosphere would still be

Normally, ecospheric availability is the focus of the fixed stock perspective, and technospheric circumstances, the focus of the opportunity cost perspective (Tilton, 1996). To illustrate, future generations may have an advanced extreme-depth extraction technology (technospheric circumstances). This technology is nonetheless useless unless there is a resource to extract (ecospheric availability). The opportunity cost approach acknowledges that *what ultimately matters* for resource availability for each generation, for each short term perspective at any point in time, is having sufficiently advanced extraction technology for the resource to be extracted. The point in the fixed stock perspective is that the pressure on future generations to have advanced extraction technologies increases as current extraction reduces ecospheric availability.[3] Because the future technosphere and its extraction technologies are, to large extent, non-foreseeable,[4] the technospheric contingency makes the opportunity cost perspective less useful in long term perspectives. Conversely, the fixed stock perspective has virtues in the long term, even though it only assesses a necessary, but not sufficient, prerequisite for resource availability.

An analogy can be made to the benefits and sacrifices of midpoint and endpoint indicators (Bare et al., 2000). Endpoint indicators generally have higher relevance but are complex and uncertain since they model mechanisms closer to the AoP (Bare et al., 2000). Midpoint indicators do not model all mechanisms that are relevant to resource availability. On the other hand, they have the benefit of introducing less uncertainty and complexity regarding what cannot be known, in this case, future technospheric circumstances. Thereby, they provide more certainty regarding the parts of resource availability which can be known, in this case ecospheric availability.

5.1.3. Influence of assessment methodology on effects of RE measures

In Paper III, it was seen how resource assessment methods value the effects of a commercial reuse operation for laptops differently. Metals for which functional recycling is available in waste electrical and electronic equipment (WEEE) treatment, such as precious metals and copper, were emphasised in particular by methods based, to large extent, on ecospheric factors. Reserve-based methods, to larger extent, emphasised metals for which functional recycling is lacking in WEEE treatment, such as

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needed even in a perfectly circular economy to respond to demand and make up for inevitable losses losses (Korhonen et al., 2018; Reck and Graedel, 2012) it makes sense to assess impacts on ecospheric availability, at least as a part of assessments of total availability (ecospheric + technospheric).

[3] And, from a sustainability perspective, it is perhaps questionable to simply assume that such technologies may be at the disposal of future generations, or refer to the opportunity cost of extraction, implying that, perhaps, great sacrifices (high opportunity costs) may have to made to ensure resource availability.

[4] One may however assume backstop technologies such as extraction from common rock as the EPS method (Steen, 1999) but the uncertainty here refers to the extraction technologies before such worst case scenarios.

tantalum and indium. Thereby, the increased recycling of laptops which was enabled by the commercial reuse operation, was given more credit by methods based, to large extent, on ecospheric factors than by reserve-based methods. According to Berger et al. (2020), reserve-based methods address the question of potential availability issues for a product system in the medium term. The results of Paper III thus suggest that use extension is important to reduce potential medium term scarcity. However, as seen in Paper II, the uses of metals for which functional recycling is lacking may only be reduced to a limited extent, or even increase, in e.g. repair. Thereby, to reduce potential medium scarcity, the results of Paper II and III imply that it could be important to develop functional recycling for such metals.

Because no additional metal input is required for use extension through reuse, resource assessment methods merely change the degree of impact reduction (Paper III). For measures which do require additional metal input, e.g. repair (Paper II) or modular designs of smartphones (Proske et al., 2016), it is plausible that choice of resource assessment method could change the rankings between measures. This calls for either deliberate choice of question and, consequently, resource assessment method with consideration to the goal and scope as suggested by Berger et al. (2020) or use of complementary methods as in Papers III and VI.

In addition to development of functional recycling for a larger diversity of metals, another way to reduce medium term scarcity could be sharing of metal-diverse products. In Paper I, it was discussed that the measure of *sharing* does not change the environmental impacts unless it allows for more function to be derived from each product, and that it is questionable whether this is the case for e.g. cars which tend to be utilized for their entire technical lifetimes (since sharing will only make cars reach their technical lifetime, which is usually limited by distance driven, in a shorter period of time). This insight is a result of LCA being static, in which all impacts of a product's life cycle are viewed as occurring simultaneously at an arbitrary point in time. In terms of mineral resource scarcity, LCA has mostly focused on long term scarcity, i.e. depletion, for which a static perspective does not need to be a weakness. However, as regards mineral resource scarcity in short and medium term, it is likely that measures such as sharing could be influential. For instance, in the case of lithium, which is most notably limited in the short and medium term (Kushnir and Sandén, 2012), sharing of electric vehicles could alleviate demand and, thereby, potential scarcity in these temporal scopes. To illustrate, if electric vehicles can largely be shared instead of privately owned, less lithium would be required to satisfy a certain transportation requirement in the next few years. Thus, sharing is unlikely to notably alter the effects of RE measures in terms of depletion, i.e. long term scarcity, but it may very well alter the effects of RE measures in terms of short and medium term scarcity.

5.2 Implications for industry and policy

Given the increasing attention to mineral resource scarcity both within policy and industry some implications of this thesis are here discussed.

Paper I, the synthesis of life cycle-based assessment studies, could confirm that products tend to become increasingly metal-diverse, among other reasons, as an effect of implementing RE measures. While measures such as lightweighting of vehicle components can e.g. reduce climate change impacts they can often come at the cost of increased mineral resource scarcity impacts. It is important for both policy and industry to be aware of this burden-shifting so that measures can be taken to mitigate it as much as possible.

Paper II, the MFA study, showed that RE measures are likely to result in decreased use of some metals at the cost of increased use of other metals. For instance, in order to extend the use of smartphones through repair, and thereby reduce the uses of many metals, the uses of indium and yttrium were indicated to increase. Accordingly, it was suggested in Paper II that mitigating mineral resource scarcity in complex, metal-diverse products may require industry and policy to focus on reducing the use of some metals and deliberately increase the use of others. Similarly, the strategy to design smartphones in a more modular fashion to facilitate RE measures based on use extension requires increased use of connectors between modules. In electronics, this typically requires additional use of gold, neodymium and beryllium, referred to by (Schischke et al., 2019) as "modularity materials".

Modularity metals, as well as metals in frequently replaced components, could be metals which industry and policy could deliberately increase the use of in order to decrease the use of others. However, such prioritizations need to be carefully considered. Using ADP-UR, which has a high CF for gold, this modular design was not favorable in terms of depletion even though it enabled use extension (Proske et al., 2016). On the other hand, that study did not account for differences in collection rates between use extension (EXT) and business-as-usual (BAU) alternatives. If this were accounted for, it is plausible that the increased functional recycling typically enabled in EXT alternatives (Paper II and III) could compensate for the increased gold use in modular smartphones, thus making the EXT favorable compared to the BAU alternative. It is also plausible that another principle of prioritization, by which gold is less prioritized than by ADP-UR, could render the EXT favorable compared to the BAU alternative. To conclude, if the metals in commonly replaced components or connectors between modules are prioritized (for whatever reason) it could be sensible for policy to support their functional recycling. If not, they could be examples of metals which industry and policy could deliberately increase the use of in order to decrease the use of other, more prioritized, metals.

Many of the metals which in this thesis have been observed to have high losses and considerable mineral resource scarcity impacts are regarded as critical for the EU. Recent EU policy recommendations (European Commission, 2020) promote substitution and recycling of critical mineral resources in order to reduce dependency on imports and, thereby, criticality. As regards recycling specifically, both WEEE and end-of-life vehicles (ELV) directives have mass-based targets. Since metals which are often considered critical are typically used in low concentrations, their recycling is not incentivized in these policy directives. Suggestions for how to incentivise recycling of critical mineral resources are, for instance, setting recycling targets for specific critical mineral resources and collection targets for specific products with higher content of critical mineral resources (European Commission, 2020).

Furthermore, as demonstrated in this thesis, the effects of RE measures on mineral resource scarcity vary considerably depending on the principles of prioritization which are applied. It is important that there is an awareness in policy and industry that choice of method can be decisive for whether RE measures are indicated to be favourable or not compared to BAU alternatives. This finding and the clarifications with regard to principles of prioritization could stimulate deliberate and well-informed choices of methods with respect to which questions are considered most relevant in specific contexts. For instance, in the case of technologies implemented at large scale it could be valuable for policy and industry actors to balance considerations of both short term and long term impacts. This could help to identify resources which are relatively unconstrained in the short term (low supply disruption probability) and with relatively low potential depletion impacts.

The Crustal Scarcity Indicator (CSI) (Paper IV) offers practitioners an LCIA-method on which to prioritise metals in terms of their potential long term scarcity impacts. Compared to other methods, its actual scope is well aligned with its intended scope, it is easy to understand and covers a wide variety of mineral resources. These features are conducive to purposive decision-making where the impacts of products on long term mineral resurce scarcity is relevant. In contexts of potential burden-shifting between mineral resource scarcity and other environmental impacts, the availability of a robust and methodologically consistent method is crucial for decision-making.

CA and hybrid methods can be useful for industry actors to assess potential for, and consequences, of supply disruption of technospheric flows. However, from the perspective of most CA and hybrid methods, only complete substitution is seen as a way to reduce probability of supply disruption. In other words, reducing the mass of a metal in a product system is not regarded as a way to reduce probability of supply disruption. Hence, even if a company would, for instance, increase the share of recycled metal to reduce the mass of primary metal required, this would not change results related to supply disruption impacts as assessed by most CA and hybrid methods. The ESSENZ method is one exception where the used amounts do impact the relative probability of supply disruption.

As demonstrated in Paper VI, it is important for companies to conduct CA studies of their own as opposed to being (mis)guided by national or supranational CA studies. This is indeed not surprising considering that criticality depends on the conditions of specific stakeholders and that individual companies have in-depth knowledge about for instance substitutability of metals in their products. Nevertheless, the point deserves being made given the ambition of some hybrid methods to e.g. include substitutability scores in CFs (e.g. (Cimprich et al., 2018)).

5.3 Implications for future research

The finding that RE measures applied to metal-diverse products are likely to increase the use of some metals and decrease the use of others naturally opens up for the question: which ones are typically increased and decreased? This thesis has shown that metals for which functional recycling is available tend to benefit more from RE measures than those for which it is not, at least when actors source products for potential use extension or take life cycle responsibility for products as commonly done in product-service systems (PSS) solutions. It has also been shown that metals in frequently replaced components such as indium and yttrium in smartphone screens are likely to increase as effect of smartphone repair. Further work could investigate which metals are typically increased in other product categories as effects of RE measures by focusing specifically on e.g. metals in commonly replaced components or modularity materials. Use of metals like gold in electronics may, on one hand, decrease due to increased collection into functional recycling and on the other hand, decrease due to being a modularity material. As implied by Paper II, additional inputs of metals for which there is functional recycling could be good candidates for increasing the use of in order to decrease the use of others, provided that collection rates are high.

In the context of comprehensive assessment of mineral resource scarcity, it was recommended in Paper V to distinguish between stock, fund and flow problems of mineral resources. This was argued beneficial in order to create better alignment between intended and actual temporal scopes within methods and between methodologies, resolve methodological inconsistency with regard to cause-effect chains and provide the literature with a more accurate terminology.

Ecospheric stock factors such as geological stocks or crustal concentrations, are the most relevant to use when intending to assess scarcity in long term scopes (as also explicated in 5.1.2 Assessment of mineral resource scarcity). Factors representing flows, such as extraction rates from specific countries, or circumstances which can influence the magnitudes of such flows, such as trade barriers are the most relevant for scarcity in the short term. The dynamic nature of such factors implies that they ought to only be included in methods addressing short term scopes, such as CA and hybrids. Mineral resources in end-of-life products are best described as funds since they depend both on the input of end-of-life products and the output of recycled resources. Fund-type compartments are the ones providing secondary resources, and are thus, the ones a circular economy must increasingly explore and extract from. In addition to assessment of long term stock problems, predominantly assessed by LCA, and flow problems predominantly assessed by CA and hybrids, methods which reflect the relative rarity of metals in different types of fund-type compartments of mineral natural resources such as end-of-life products and landfills could be useful in a comprehensive assessment of mineral resource scarcity (Table 5). Extraction rates from funds of secondary resources would, like global primary extraction rates, be considered flows. The lack of consideration of supply risks related to such secondary mineral resource flows has been pointed out as an important limitation of hybrid methods (Berger et al., 2020).

Questions regarding resource availability in secondary (fund-type) compartments are often studied by means of dynamic MFA. A comprehensive assessment of mineral resource scarcity could thus comprise the complementary use of LCA for assessing stock problems, MFA for fund problems and CA for flow problems of mineral resources (Table 5). Dynamic MFA is sometimes referred to as dynamic stock and flow modelling. Clearly, this terminology differs from the terminology suggested in this thesis, which would rather refer to it as fund and flow modelling. This discrepancy relates to the fact that the distinctions between stocks, funds and flows are not clear-cut. Consequently, how to clearly distinguish between these categories is an open question (Sonderegger et al., 2017). Hence, a topic for future research could be to clarify which natural resource categories best describe different compartments of mineral resources. Further, whenever these methodologies are used in a complementary manner for comprehensive assessment of mineral resource scarcity it could be important to agree upon a common terminology or at least be aware of differences among the methodologies.

Related issues have been discussed by Beylot et al. (2020) who review life-cycle based studies which aim to account for dissipation. Among other things, they stress the influence of temporal perspective in characterizing flows as dissipated or not. With a short term perspective, all metals which are not functionally recycled can be considered dissipated (Beylot et al., 2020). With a medium or long term perspective, however, it cannot be excluded that even such non-functionally recycled flows may become functional again (Beylot et al., 2020). Thereby, the temporal perspective has implications for the categorization of mineral resource compartments as stocks, funds and flows. The above suggested work in clarifying which natural resource categories best describe different compartments of mineral resources and in what temporal perspective (Beylot et al., 2020) could add detail to the simple overview in Table 5.

Complementary use of LCA, MFA and CA has already been demonstrated to be a valuable approach by Bobba et al. (2020) for studying such complex issues as environmental impacts, implications of RE measures and potential supply disruption impacts. They concluded that LCA and MFA are relevant for assessing environmental impacts of scenarios of RE measures while CA could complement as a screening of which resources to focus on in particular. This conclusion differs from what is suggested in this thesis regarding *how* methods can complement each other. Nonetheless, it confirms that complementary methods are valuable in assessments of complex systems where several concerns are relevant.

Table 5. Overview of potentially complementary methodologies for mineral resource scarcity assessment.

Resource category	ecospheric stocks	technospheric funds	technospheric flows
Renewal (+)	n/a	products reaching end-of-life	primary and secondary extraction
Reduction (-)	extraction (primary)	dissipation and extraction (secondary)	political instability, trade barriers etc.
Temporal relevance	long term	medium term	short term
Methodology	LCA	MFA	CA

CHAPTER 6 - Conclusions and recommendations

This thesis has contributed to knowledge on assessment of mineral resource scarcity in a circular economy context by studying RE measures from a life cycle perspective, comparing principles of prioritization between metals on which mineral resource scarcity impacts are assessed, and, analysed how such principles of prioritization can affect conclusions regarding RE measures applied to metal-diverse products.

There are a number of product system characteristics which are decisive for the effects of real-world configurations of RE measures in terms of mineral resource scarcity: physical (e.g. material diversity); related to product chain efficiency (e.g. reuse, component replacement, collection and recycling rates); temporal (e.g. pace of development of new products and whether products tend to be used for their full technical lifetimes).

It can be confirmed that RE measures which increase product complexity in order to e.g. achieve more durable or lightweight designs can shift burdens from e.g. climate change impacts to mineral resource scarcity impacts. RE measures such as reuse of laptops, repair of smartphones, long-life designs of LED lighting products have the potential to reduce mineral resource scarcity impacts. Reductions from such measures are typically attributed to two key features: use extension and increased collection rates into functional recycling. This implies that metals for which functional recycling is available are the ones which generally benefit most from configurations of RE measures. The uses of metals for which functional recycling is lacking are reduced to considerably less extent. There are also risks that metal use increases as effects of RE measures. In particular, there is risk of increased use of metals for which functional recycling is lacking, especially if they are present in components with high replacement rates or if products designed for long life are replaced before reaching their technical lifetime due to rapid pace of development of newer products. This implies that in addition to measures based on e.g. use extension, recycling needs to become more adapted to the metal diversity of modern products in order for the circular economy vision to deliver according to expectations. Further, because rankings between RE measures provided by R-frameworks can easily shift depending on these product systems characteristics, implementation of RE measures is better informed by analysis and consideration of product system characteristics than by R-frameworks.

Because of these varying effects, and the potential increase of some metals, understanding the principles of prioritization of resource assessment methods used is crucial for RE measures to have the intended effect. Because the prioritizations are so different it is plausible that choice of method can change the ranking between RE measures based on use extension and business as usual.

However, since mineral resource scarcity is inherently both technospheric and ecospheric there is a variety of questions to address. Because of this, there has been a persistent debate on which questions are most relevant and how to assess them. Consequently, there is an abundance of different methods to choose from, of which many methods are methodologically ambiguous and inconsistent. Further, concepts such as depletion, criticality, scarcity and rarity are frequently confused in the literature. Comparing the methodologies LCIA, CA and hybrid methods in terms of a common framework of cause-effect chains allowed for clarifying the relations between such concepts. In long term scopes, as predominantly assessed in LCIA, scarcity is caused by ecospheric rarity and largely non-foreseeable demand. In short term scopes, as predominantly assessed in CA and hybrids, scarcity is caused by technospheric rarity and largely foreseeable demand. Further, the predominant scopes can be summarized as follows:

- Depletion LCIA methods reflect the potential of current product systems to deplete ecospheric stocks, and ultimately cause potential scarcity in the long term future.
- Future efforts LCIA methods include what is reflected by depletion methods, i.e. potential scarcity, and add potential *consequences of scarcity* in terms of substitution to lower grade ores and associated increased costs.
- Hybrid methods reflect the potential of technospheric circumstances to disrupt supply of technospheric flows and thereby cause scarcity in the short term future.
- CA methods include what is reflected by hybrid methods, i.e. potential scarcity, and add potential *consequences of scarcity* in terms of substitution to other resources and associated increased costs.

Further, for a comprehensive assessment of mineral resource scarcity, it is useful to recognize that mineral resources can pose stock, fund and flow problems. This distinction can resolve methodological inconsistency, align actual and intended temporal scopes and provide a more accurate terminology. Thereby, it could serve to reconcile misunderstandings in the persistent debate on mineral resource scarcity so that complementary methods can be developed and used in a comprehensive assessment.

Based on these conclusions, it is recommended that mineral scarcity intending to assess:

- Long term scopes, are addressed by focusing on factors representing ecospheric stocks such as crustal concentrations. The crustal scarcity indicator developed in Paper IV address the need for such an LCIA-method.
- Short term scopes, are addressed by focusing on factors representing technospheric flows or circumstances which can disrupt them such as extraction rates and trade barriers. This is generally the focus of CA and hybrids.
- Medium term scopes, are addressed by focusing on factors representing funds such as reserves, resources in end-of-life products and landfills. Funds representing secondary

resources are expected to become increasingly important with the advent of the circular economy. The development of technospheric fund methods could be useful additions to a comprehensive assessment of mineral resource scarcity.

The conclusions regarding effects of RE measures vary greatly depending on the principles of prioritization of resource assessment methods.

Using MFA, where the implicit principle of prioritization is that potential scarcity of each metal poses a unique problem, it cannot be concluded whether e.g. smartphone repair reduces mineral resource scarcity, because uses of metals which typically increase, indium and yttrium, cannot be compared with the decreased use of other metals.

Prioritizations of LCIA-methods vary considerably. In the case of laptop reuse this affects which metals are emphasised, and also, as a result, the degree of impact reduction. Metals in laptops which are functionally recycled in current WEEE treatment, such as gold and copper, are prioritized to a greater extent in LCIA-methods which are comparatively more ecospherically oriented than they are in methods which are comparatively more technospherically oriented (e.g. based on reserves). As a result, the more ecospherically oriented LCIA methods result in a higher degree of impact reduction. In configurations of RE measures where additional metal input is required, the choice of LCIA-method can plausibly be decisive for whether they are concluded to reduce mineral resource scarcity or not compared to business as usual.

In CA methods and hybrids, prioritizations between metals are typically not related to a physical amount (the ESSENZ method is one exception). Thereby, the only RE measure credited with reducing supply disruption impacts is to change material, i.e. to substitute metals completely. In contrast to hybrids, CA methods typically also assess potential consequences of supply disruption, i.e. vulnerability to supply disruption. Thereby, they can point to metals of more specific relevance to a specific system under study.

In summary, it is concluded that RE measures tend to be able to reduce mineral resource scarcity, but exceptions exist, and effects vary greatly between metals. It is therefore recommended to consider the outlined product system characteristics which have been shown to determine the effects on mineral resource scarcity of RE measures. This also enables identification of uses of metals which might increase as effects of RE measures. Increased metal use as effects of RE measures can either be attempted to be mitigated, or deliberately accepted, motivated by some principle of prioritization.

For such decision-making, it is crucial that principles of prioritizations are distinct and purposive. This is achieved if methods intending to assess: short term scopes focus on technospheric flows (predominantly assessed within CA and hybrids); medium term scopes focus on technospheric funds; and, long term scopes focus on ecospheric stocks, such as the Crustal Scarcity Indicator developed in Paper IV. A circular economy will, by definition, increasingly depend on resources from technospheric funds such as end-of-life products and landfills. Hence, methods addressing potential scarcity related to technospheric funds could be valuable additions to a comprehensive assessment of mineral resource scarcity.

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